A systematic review of fused deposition modeling process parameters

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Abstract

Fused deposition modeling (FDM) is an additive manufacturing technique with significant advantages, including cost effectiveness, applicability for a wide range of materials, user-friendliness and small equipment features. However, its poor resolution represents a hindrance for functional parts for commercial production. In this review, the key process parameters are presented with their factors and effects on the characteristics of FDM-printed polymeric products. Hence, better insights into the relationship between key parameters and three main printing characteristics, namely, surface roughness, mechanical strength and dimensional accuracy, in existing FDM research are provided. A conclusion that addresses the challenges and future research directions in this area is also presented.

Keywords: Additive manufacturing, fused deposition modeling, process parameters, polymers, characteristics

INTRODUCTION

Industry 4.0 has encouraged the development of advanced additive manufacturing technologies¹,² with the ability to simplify a whole fabrication process into one step, produce complex designs, reduce the production cycle time and cost³ and increase the reproducibility. This development has therefore enabled their wide application in the pharmaceutical, biomedical, soft robotics, flexible electronics, aerospace, automotive and architectural industries. Fused deposition modeling (FDM) has gained significant
popularity as it has important advantages, such as being cost-effective in terms of the printer and material used, a wide range of applicable thermoplastic materials and user-friendly and small equipment features\(^4\). However, its applications, especially regarding functional parts, are limited because of its poor resolution\(^5\) that affects the surface quality and poor mechanical strength and dimensional accuracy. These limitations represent strong hindrances to commercial production, which requires adequate high-precision and stable qualities to meet product requirements.

Numerous researchers have carried out studies to analyze the key parameter effects to achieve desirable properties for FDM-printed products\(^6,7\), with many of them using various statistical tools. A large number of conflicting FDM parameters that influence the characteristics of the printed product are impediments in determining the optimal parameters to use\(^8,9\). Although the effect of FDM process parameters has been extensively covered in recent studies\(^2,6-8\), none of them have visualized the factors of parameter selection, direct-indirect effects and their relationship in a systematic manner for better understanding.

In this systematic review, the research related to FDM process parameters from 2013 to 2021 is used as a reference. In Section 2, a brief explanation of the definition, factor and effect of key parameters is presented, before further focusing on their relationships toward the characteristics for fabrication. To demonstrate a better understanding of the influence of key process parameters on multiple part characteristics, an overlap mind map and graphic illustration are provided. In Section 3, three main effects on characteristics, namely, surface roughness, mechanical strength and dimensional accuracy, are discussed in detail. In Section 4, the remaining significant challenges, which contribute to the part characteristics, are discussed. In section 5, the current progress is addressed and the overall findings are concluded.

**Overview of FDM process**

FDM is a technique that utilizes a heating element to heat up a continuous filament made of a thermoplastic polymer from a solid to a molten state, which enables layer-by-layer material deposition via a moving nozzle head and solidifies after cooling to room temperature to build the part. The filament material should be sufficiently stiff and rigid during the extrusion process to prevent buckling owing to the pressure generated during the feeding process. The thermoplastic filament extruded through the printing nozzle displays viscosity levels that are sufficiently low to assure the flowability of the melt. When semi-liquid thermoplastic filament materials are extruded from a nozzle on the printing platform, they do not immediately solidify. Instead, these semi-liquid thermoplastics, for a specific layer under construction, fuse together before curing/solidifying into a layer-wise stacked part at ambient temperature. In the post-deposition stage, one layer remains molten, lying at the interface between adjacent deposited layers must able to interdiffuse across the interface, to ensure a good level of interlayer adhesion due to the molecular interactions. Figure 1 illustrates FDM and the main features required for proper material extrusion\(^12\).

The FDM process commences with a relevant slicer software. Firstly, a three-dimensional (3D) digital model is created with any design software, such as Solidworks, Catia, Rhino or Inventor, and the design is finalized with optimization using computer-aided design (CAD) and analysis software according to the printer specification. The 3D digital model is then converted to a printer recognized format file (e.g., a stereolithography file or OBJ). The file is imported into the printer software and the model to be printed is configured. Slicing software is utilized with all the printing requirements are included. This configuration contains the material selection and the nozzle size of the printer. The software also separates the model into layers and the printing quality and movement commands can be configured. The specific procedure for fabrication is carried out according to its working principle and layer-by-layer printing is developed until the complete fabrication of the 3D printed model.
Bond formation mechanism

The thermal energy of the semi-molten material drives the development of bonding in the FDM process. The degree of interlayer and intralayer bonding is critical in determining the characteristics of the product\textsuperscript{[13]}. In the solidification process, the cross sections of the beads are originally idealized as circles. Their molecules generate interfacial molecular contact through wetting [\textit{Figure 2(1)}] and then move toward preferred configurations to achieve adsorptive equilibrium. Molecules diffuse across the contact, generating an interfacial zone and/or reacting to form primary chemical bonds across the interface\textsuperscript{[14]}. A neck growth is formed [\textit{Figure 2(2)}], which is a kind of bridging formed by viscous sintering between two adjacent beads. The magnitude of neck growth and molecular diffusion reflect the quality of the bond formation [\textit{Figure 2(3)}]\textsuperscript{[15]}. The intra- and interlayer bonds and neck size all influence the part strength. The sintering is the phenomenon involving coalescence of the particles and is mainly driven by two temperature-
dependent properties which is surface tension and viscosity.

**Application of FDM products**

This manufacturing technology offers a broad range of part production options due to its ability to create complicated parts and their flexibility. FDM may be used to produce a variety of applications that require rapid and affordable parts or rough and stiff products for end customers. The following examples illustrate some of the available parts with their applications that were fabricated by FDM:

In the aerospace industry, including aircraft, drone parts and rockets, FDM manufactured parts are used to replace traditional metal components that can reduce their weight whilst maintaining appropriate robustness and reducing the turnaround time for part repair. Stratasys adopted FDM for rapid prototyping, manufacturing tooling and part production in collaboration with various aerospace companies, such as Piper Aircraft, Bell Helicopter and NASA. For example, NASA printed 70 components of the Mars rover using Stratasys FDM technologies to obtain a lightweight and strong structure. Bell Helicopter manufactured polycarbonate wiring conduits for their V-22 Osprey using FDM whilst reducing the manufacturing time to 2.5 days (from 6 weeks) [16]. Stratasys and Aurora Flight Sciences utilized ULTEM 9085 resin and FDM technology, where a honeycomb internal structure was used inside the internal wing design. Boeing uses FDM parts for its 777-300 ER door handles and camera cases.

In architecture, the first 3D printed residential construction, known as the 3D Print Canal House, was built in Amsterdam in 2014 by Dus Architects using the FDM process. The house was printed using a thermoplastic material (a biodegradable plastic in this case). The project managed to demonstrate the mobility of the printer, how 3D printing could revolutionize construction by increasing the efficiency and the rapid building of low-cost housing whilst reducing pollution and waste [17].

FDM has also been used to assist with personalized medicine and customizable implants for various medical applications. Customized tracheal stents fabricated by FDM are less expensive and have better surface quality [18]. An anatomically shaped lumbar cage for an intervertebral disc fabricated by FDM was physically characterized to ensure its compatibility for load bearing applications as a spinal implant [19]. In addition, FDM has been extensively used for scaffoldings and tissue engineering. In the pharmaceutical industry, FDM, in combination with hot-melt extrusion (HME) and optimized formulation compositions, has recently proven to be a viable solution for the production of pharmaceutical tablets and implants with variable drug release patterns. We refer the reader to the latest reviews from Caileaux *et al.* and Chen *et al.* for further details on these applications [20,21].

**PROCESS PARAMETERS IN FUSED DEPOSITION MODELING**

The main process parameters are described below and depicted in Figure 3 [22,23].

**Nozzle diameter**

The nozzle diameter is the diameter of the extruder tip and depends on the type of nozzle used [24]. The extruder nozzle diameter has an impact on the extruded melt flow behavior. Basically, the filament encounters a high shear rate at the nozzle and a low shear rate when deposited on the bed during the FDM process. The pressure drop can increase due to flow instabilities caused by variations in shear rate throughout the nozzle diameter [25]. The selection of an optimal nozzle diameter is critical for maintaining a proper and consistent flow of the extruding material. As the outlet nozzle diameter becomes narrower, the pressure drop increases [26]. Compared to a narrow diameter, the pressure drop caused by larger nozzle diameters provides consistency of the applied raster width and thus affects the accuracy of the finished
Figure 3. Illustrations of process parameters, including layer thickness and Raster width, build orientation and FDM tool path parameters. Layer thickness and Raster width, reproduced with permission\cite{22}, Copyright 2022, Springer. Build orientation, reproduced with permission\cite{23}, Copyright 2017, Springer. FDM tool path parameters, reproduced with permission\cite{11}, Copyright 2015, Springer.

printed parts. The decrease in the nozzle diameter contributes to better resolutions with low layer thickness, which in turn provides a good surface quality. The recommended guideline for the maximum layer height is not more than 80% of the nozzle diameter. This is because the extruded materials need to be pressed in order to fuse them. The larger the nozzle diameter, the shorter the time it takes to complete the item.

Although there was no linear correlation, a larger nozzle hole diameter was found to increase the density and tensile strength of the products\cite{27}. By increasing the nozzle diameter, more molten material may be deposited to fill the volume, causing the product to become solid with a narrow distance between infills. The small nozzle diameter demonstrates that the distance between infills has a wide gap, resulting in many voids between layers. The tensile strength of the printed product increases as the interlayer cohesion is increased when using a low layer thickness via a smaller nozzle diameter.

**Extrusion and bed temperature**

The extrusion temperature is the temperature used to convert the solid filament into a molten state before the extrusion process and depends on the material type and printing speed. It should be set based on the melting point of the filament material\cite{28}. The bed temperature is the temperature of the heating element that places the printed product model\cite{29}. During the extrusion process, the thermoplastic materials are in a viscoelastic state and high temperature enables the stretching and alignment of polymer chains in the direction of the material flow through the extrusion nozzle. The material begins to cool and solidify as soon as it exits the extrusion nozzle. The hot material from the extruder nozzle is deposited onto the previously extruded layer, which, in the process of cooling, causes the latter to reheat. Rapid heating and cooling can cause non-uniform thermal gradients and increase the internal stress, which will pull the underlying layer upward and cause it to distort.

The extrusion and bed temperatures are related to the dynamic cooling of viscous polymer melts. Thus, the final properties of the printed parts are dependent on the stress relaxation and polymer chain diffusion in this cooling process, which can have a positive influence on the part quality and its strength. The temperature increases around the crystallization temperature at the interface of the adjacent bead, allowing appropriate bonding to form. The previously deposited layer should be sufficiently heated around the crystallization temperature to allow for molecular chain rearrangement during deposition of the melting
filament. The higher temperature of the previously deposited filament could cause the molten material to rapidly flow and the deformation of subsequent deposited layers to occur. At lower temperatures, the molecular chain of the deposited material does not have sufficient time to be rearranged and undergo stress relaxation, thereby causing lower bonding of the two adjacent beads.

Heated beds help to prevent rapid residual stress relaxation during the printing process due to a change in the ambient temperature. This leads to different thermal effects on the quality of the build parts. The quality of the printed parts is also dependent on the diffusion at the joints among the beads, which is dependent upon the shape of the beads and might be caused by the direction of the heat transfer. Basically, the heat transfer occurs from the higher temperature region to a lower temperature region. Smaller differences in the bed and ambient temperatures can reduce the thermal gradients, resulting in shape errors caused by the decreased heat shrinkage of the printed product. It is noteworthy that the bed temperature should be as close to the material softening temperature as possible in order to minimize warpage or shrinkage due to thermal stress reduction. The printing bed should be heated to a certain temperature range to improve adhesion and prevent deformation caused by shrinkage during the solidification process.

**Print speed**
The print speed is the distance travelled by the nozzle tip per unit time (mm/s) during the printing process. The optimum printing speed in FDM is determined by the material, extrusion temperature and resolution used.

Higher printing speeds result in smaller heat transfer windows, which might lead to the extrusion of a partially melted extrudate. This has a significant impact on the dynamic cooling and melting rates of a material, resulting in poor layer bonding. Setting a high printing speed might lead to poor layer bonding and, as a result, a reduction in the mechanical strength of the product. Faster printing speed results in larger voids and worsened interlayer bonding. Lowering the printing speed means sacrificing the build time and printing efficiency.

To minimize melting instabilities, the nozzle temperature and printing speed should be compatible, i.e., if the extrusion temperature is too high at a slow printing speed, the melt becomes less viscous, reducing the dimensional stability and increasing the cooling time. Similarly, if the set temperature is too low at high speeds, the filament may not melt as quickly as it should (due to materials becoming stuck inside the nozzle), resulting in a melt that is much more viscous than it should be. The shrinkage issue can be reduced by using appropriate combinations of nozzle temperature and printing speed.

**Build orientation**
The build orientation is defined as the mode position part that is placed on the platform in respect of the X, Y and Z axes and can be presented as a quantitative parameter (angle of axis) or a categorical parameter (ZX-upright, XZ-edgewise and XY-flatwise). The selection of the optimum building orientation is determined based on the user’s selections of primary criteria and takes geometrical factors into account: minimizes the support structure volume and contact area. For different build orientations, the build time and number of layers required are determined. The build time increases when the build orientation changes from flat to upright. This is because the number of layers for this build orientation is significantly greater and the required build time and material used for the upright build orientation increase. This leads to an energy usage increase and higher energy costs. The part build orientation is the most important process parameter, which has a significant impact on the surface finish, dimensional accuracy, mechanical strength and post-processing requirements.
The staircase effect is minimized if the build orientation is parallel or vertical to the surface facet of the printed model. If the angle between the surface normal and the build orientation (range of 0°-90°) increases, the staircase effect is noticeable and the surface quality decreases. The areas of the part that are frequently smoothed by the extrusion nozzle but are not directly in contact with the support material and build platform achieve a fine surface finish. As a result, a 3D printed part is actually a top-facing surface and will always have a low surface roughness. As the build orientation can vary the number of layers, edge errors and layer swelling, which have an impact on the dimensional accuracy, can be avoided by properly placing the component. The build orientation affects the layer-by-layer bonding inside the printed product and can resist the load when oriented in the load direction. If the load is applied horizontally in the 0° orientation printed part or applied vertically 90° orientation printed part, the weaker bonding leads to strength failure. In addition, post-processing is required to minimize aesthetic defects due to adhesion forces that are related to the heated bead.

**Layer thickness**

The layer thickness is defined as the vertical resolution and depends on the material, nozzle diameter and type of nozzle and can influence the surface quality, dimensional accuracy, mechanical strength and build time.

While a low layer thickness will result in a good surface finish, a high layer thickness will result in a poor surface finish. This is because when the layer thickness increases, the number of layers will decrease, making the staircase effect more obvious. It is difficult to preserve the geometry inaccuracy between the printed product and the original CAD dimensions due to the staircase effect. A low layer thickness is preferable for improving the dimensional accuracy. The effect of layer adhesion on the strength of a printed object is determined by how well the individual layers of the material stick together. Thinner layers may be stronger because a shorter distance between the nozzle and the preceding layer may heat the material and a smaller amount of material aids the homogeneous heat distribution, leading to effective bonding formation. Furthermore, since the gaps between the lines of an already printed material are smaller, the density of the parts with thinner layers may be larger, leading to a stronger structure. The stiffness and strength of an FDM-printed part are not only a function of the void density but also of the number of layers. The build time is inversely proportional to the layer thickness. More build time is required for a low layer thickness.

**Raster width and angle**

The raster width is defined as the road width and depends on the nozzle diameter. A smaller raster width requires more production time and less material consumption. Larger raster widths give greater bonding area, which may increase the diffusion and result in stronger bonds. However, a larger raster can also result in stress accumulation along the width of the part and a deterioration in the thermal distribution. The thermal mass of a larger raster may be attained, allowing it to cool more slowly, which increases the
bonding between the beads and therefore enhances their strength.\textsuperscript{[34]}

The raster angle is defined as the viewpoint of the raster path with respect to the X axis in the printing platform that is attributed to the internal structure of the final printed product. The raster angle has an influence on the surface roughness and mechanical strength. The surface roughness is measured in the parallel and perpendicular directions to the tensile loading. Surface roughness values are lower when the measuring direction is parallel to the raster angle of 0° and the tensile loading. When measuring the tensile strength perpendicular to the tensile loading and parallel to a raster angle of 90°, the lowest surface roughness is obtained. From a mechanical strength point perspective, the fracture initiated from the edge and propagated until a complete fracture occurred. The crack propagates in the transverse direction to the applied force at a 0° raster angle and fracture occurs owing to the raster failure. The fracture path is also transverse to the applied force at the raster angle of 90°; however, the fracture occurs between the interlayer bonds. The interlayer bonding strength is significantly lower than the strength of the raster, which explains the higher tensile strengths obtained for the 0° raster angle.\textsuperscript{[35]} The impact of the raster angle on the build time is still unknown.

Figure 5 illustrates representative examples of the different raster angles.\textsuperscript{[36]}

Air gap
An air gap is defined as the spacing between two adjacent deposited beads in the same layer and can be categorized into three types of gaps, namely, positive, negative (overlap between two adjacent layers) and zero gaps. Positive air gaps allow for spacing between two adjacent layers, resulting in a loose interconnection structure with weak bonding between adjacent filaments, leading to lower strength. A negative air gap refers to the overlap position of two beads with strong interfacial bonding, significantly improving the strength. A zero gap means that the beads are touching each other and this type of printing is highly recommended. The roughness value improves with the reduction of the air gap.\textsuperscript{[37]} There is a space between the adjacently laid roads when there is a positive air gap. When a semi-liquid material is extruded, it might flow in an unexpected manner through the gap, causing surface variance. In a negative air gap, bump formation occurs, resulting in an uneven surface. In a zero-air gap condition, the beads are close to each other, which restricts the flow and fusion in the predicted manner.
Infill density and pattern

The infill density is defined as the percentage of material consumption used to build the internal structure of a printed product. The air gap and raster width parameters allow users to control the infill density. The density of the infill influences the mass and strength of an FDM-printed part. Lower densities require less print time and material, resulting in cost savings and weight reduction. However, when more voids are formed within the structure simultaneously, the porosity increases. Thus, the bonded area decreases as a result, resulting in poor mechanical characteristics. In contrast, the denser component has higher mechanical qualities but takes significantly longer to complete.

The infill pattern illustrates the internal geometrical layout of the printed part [Figure 6][38]. The complexity of the infill pattern affects the print time, material consumption and mechanical characteristics. For example, in the hexagonal design, each layer is laid down similarly on top of a previous layer, just like the bonding zone. In contrast, in the rectilinear pattern, the new layer crosses the previous layer at places that correspond to the bonding zone between each layer. Therefore, the design of the cross in rectilinear has higher tensile strength compared to the honeycomb pattern.

Based on a literature review, Figure 7 demonstrates a simple mind map of key parameters for better understanding.

PREVIOUS RESEARCH OF PROCESS PARAMETER OPTIMIZATION AND ANALYSIS

The process conditions must be established for each application in order to fulfill the customer needs and satisfaction. FDM has a large number of conflicting parameters that influence the part characteristics individually or in combination. Determining the optimal conditions of process parameters is critical for a significant impact on production efficiency and part characteristics. There have been tremendous research efforts to identify the influence of FDM process parameters on surface quality, mechanical strength and dimensional accuracy.

Surface roughness

Surface roughness is extensively used as an index of product quality. The staircase effect is one of the main problems in additive manufacturing to achieve good surface quality. The layer-by-layer appearance not only effects the aesthetic view but its surface characteristics are also important to ensure proper function in terms of dimensional precision and stress concentrations that can cause early failure under fatigue loading. Surface defects that may exist in FDM include the chordal effect, the residue of access material that appears between lines[39], support structure burrs and errors due to the starting and ending of deposition, leading to a poor surface finish. ASTM B46.1 is a common test to measure surface roughness and average of the absolute value of profile heights over a given length (area) are calculated. Setting optimal process
Figure 7. Mind map of factors and direct/indirect effects of process parameters. (A) Nozzle diameter; (B) extrusion temperature; (C) bed temperature; (D) print speed; (E) build orientation; (F) layer thickness; (G) raster angle; (H) raster width; (I) air gap; (J) infill density; (K) infill pattern.
parameters, either individually or in combination, can improve the surface quality of the printed part. Table 1 shows the research studies that investigated the influence of key parameters on the surface roughness in FDM printing. A detailed explanation for each important parameter is presented as follows:

### a. Effect of layer thickness on surface roughness
The surface finish of an FDM-printed product is improved by decreasing the layer thickness. The findings of Ayrilmis et al. regarding the layer thickness relationship with surface roughness contradict the findings of Reddy et al. who found that a high layer thickness leads to a better surface finish\(^\text{[40,41]}\). As layer thickness increases, amplitude and spacing of the surface profiles increases and the stair-stepping effect decreases.

### b. Effect of build orientation on surface roughness
The surface roughness increases as the build orientation angle increases\(^\text{[42,43]}\). The selection of build orientation depends on the complexity of the design that might require a supporting material for printing. A preferable build orientation is to be printed in the smallest dimension or shortest side of the target model with respect to the Z direction of the build platform, as the top surface that is extruded by the nozzle is smooth compared to the region that is in contact with the print bed, which normally has a support mark.

### c. Effect of print speed on surface roughness
The surface quality in both the horizontal and vertical directions is reduced when the printing speed increases. Slow printing speeds lead to better surface quality because they can provide more time for material deposition and fusion processes. At higher speeds, there is potential for the material not to deposit effectively and the time taken for the thermoplastic chains to diffuse and crystallize is reduced, leading to a rough quality surface. There is also a risk of deposited bead stacking up at high print speeds. The extrusion of a material is inhomogeneous and insufficient at high print speeds. The amount of material deposition significantly influences the surface topography using a layer thickness of 0.2 mm, as shown in Figure 8\(^\text{[44]}\).

### d. Effect of extrusion temperature on surface roughness
An increment in the extrusion temperature decreases the surface roughness, which is due to a reduction in viscosity. The low viscosity leads the extruded bead to lose shaping control (the desired shape is a sectional circular shape) and form an oval shape. The oval shape generates a wider contact area between layers, resulting in low surface roughness. The higher temperature produces more bulging as more material is laid down from the nozzle and when it rounds off by the contact area between layers, better surface quality can be obtained.

### e. Influence of raster-related parameters and air gap on surface roughness
The surface roughness can be reduced by increasing the raster width. For air gaps, the best condition is zero. However, in reality, even though a zero physical gap is set at the printer, it is difficult to obtain a zero physical gap. Negative air gaps (overlap condition) may reduce the surface roughness because less voids between beads result in a smoother surface construction.

### f. Short discussion and summary of key parameters related to surface roughness
Layer thickness is the most favored and influential factor in FDM. According to Anitha et al. layer thickness has a significant impact on surface roughness, contributing 51.57%, followed by raster width (15.57%) and print speed (15.83%)\(^\text{[45]}\). Nidagundi et al. highlighted that layer thickness, build orientation, and fill angle contribute about 88.45%, 7.55%, and 4.09% to surface roughness, respectively\(^\text{[46]}\). The statement that layer thickness has a strong relationship with surface roughness was supported by findings from other research studies\(^\text{[47,48]}\). For both low and high layer thicknesses, there is no clear guideline for selection in achieving good surface quality. Basically, it depends on the gaps between layers being the main cause of surface roughness. The top printed
| First authors         | Year | Reference | Method                                          | Mat. | Fix item                  | Variable item                                                                 | Optimum value                                                                 |
|----------------------|------|-----------|-------------------------------------------------|------|---------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Ognjan Lužanin       | 2013 | [120]     | ANOVA, Half-normal plot, Residual Plots, Main Effects diagram, geometric interpretation | PLA  | (1) Infill density = 15% (2) Number of contours = 2 (3) Layer thickness = 0.1mm Print speed = 100 mm/s | (1) Extrusion temp = 225, 230, 235 °C Print speed = 40, 60, 80 mm/s (1) Extrusion temp = 235 °C (Highest) Print speed = 40 mm/s (Lowest) | 1.5511                                                                        |
| Maruthi Prasad       | 2014 | [121]     | Full factor experiment, Box-Behnken design, ANOVA, RSM, genetic algorithm | ABS  | (1) Air gap = 0 mm Contour width = 0.464 mm | (1) Layer thickness = 0.127, 0.178, 0.254 mm (2) Build orientation = 0, 15, 30 (3) Raster angle = 0, 30, 60 (4) Raster width = 0.4064, 0.4564, 0.5064 mm Air gap = 0, 0.004, 0.008 mm (1) Layer thickness = 0.25 mm (Highest) (2) Build orientation = 15° (3) Raster angle = 30° (4) Raster width = 0.5063 (Highest) Air gap = 0.004 mm (2) Print speed = 16 mm/s (Lowest) Infill density = 20% (Lowest) | 3.046                                                                         |
| Stephen O. Akande    | 2015 | [122]     | Factorial design, Pareto chart, DFA             | PLA  | Not reported               | (1) Layer thickness = 0.25, 0.50 mm (2) Print speed = 16, 21.33 mm/s Infill density = 20%, 100% | (1) Layer thickness = 0.25 mm (Lowest) (2) Print speed = 16 mm/s (Lowest) Infill density = 20% (Lowest) | 2.46                                                                          |
| Vijay.B.Nidagundi     | 2015 | [46]      | Taguchi's L9 orthogonal array, Main effect plot of S/N ratio, ANOVA               | ABS  | Not reported               | (1) Layer thickness = 0.10, 0.20, 0.30 mm (2) Build orientation = 0, 15, 30 (3) Fill angle = 0, 30, 60 | (1) Layer thickness = 0.1 mm (Lowest) (2) Build orientation = 0 (Lowest) (3) Fill angle = 0 (Lowest) | 0.3410                                                                        |
| Francesca Chaidas    | 2016 | [123]     | Direct experimental effect                   | PLA  | Not reported               | (1) Contour width = 1, 2, 3 mm Extrusion temp = 210, 220, 230 °C | (1) Contour width = 2 mm (2) Extrusion temp = 230 °C (Highest)                  | 12.84                                                                         |
| Kishore              | 2018 | [124]     | ANOVA, Multiple Regression Analysis           | PLA  | Not reported               | (1) Layer thickness = 0.06, 0.08, 0.10, 0.12 mm (2) Build orientation = 0, 45, 60, 90° (3) Infill density = 20, 30, 40, 50% | (1) Layer thickness = 0.12 mm (Highest) (2) Build orientation = 45° (3) Infill density = 40% | 2.25                                                                          |
| Kovan                | 2018 | [125]     | Direct experimental effect                   | PLA  | (1) Print speed = 60 mm/s (2) Bed temp = 65 °C (3) Infill density = 35% | (1) Layer thickness = 0.10, 0.20, 0.40 mm (2) Extrusion temp = 190, 210, 290 °C | (1) Layer thickness = 0.10 mm (Lowest) (2) Extrusion temp = 210 °C | 7.8                                                                           |
| Velineni             | 2018 | [126]     | Full factorial design, ANOVA, Pareto           | PLA  | (1) Extrusion temp = 260 | (1) Layer thickness = 0.1, 0.2, 0.3 mm | (1) Layer thickness = 6.12-7.22 |
| Authors          | Year  | Methodology                        | Material   | Factors                                                                                           | Results |
|------------------|-------|------------------------------------|------------|---------------------------------------------------------------------------------------------------|---------|
| Vinaykumar S Jatti | 2019  | Direct experimental effect         | PLA        | (1) Nozzle diameter = 0.4 mm  
(2) Print speed = 60, 80, 100 mm/s  
(3) Build orientation = 0, 45, 90 °C  
(4) Extrusion temp = 190, 200, 210, 220, 230 °C | 10      |
| Mishra           | 2019  | Taguchi L27 Orthogonal, ANOVA, S/N ratio, regression analysis | ABS Post-processing = Chemical treatment | (1) Raster angle = 0, 45, 90  
(2) Raster width = 0.3556, 0.5306, 0.7306 mm  
Air gap = 0, 0.05, 0.10 mm | 5.74    |
| Jianglou Jiang   | 2019  | Direct experimental effect         | PLA        | (1) Layer thickness = 0.20 mm  
(2) Shell thickness = 0.80 mm  
(3) Fill density = 0%  
(4) No support types  
Print speed = 30 mm/s | 0.057   |
| Yunus            | 2020  | Direct experimental effect         | ABS+P430   | (1) Infill density = 60%  
(2) Infill pattern = crossed  
45°  
(3) Layer thickness = 0.10 mm  
(4) Nozzle diameter = 0.60 mm | 3.9     |
| Sammaiah         | 2020  | Direct experimental effect         | ABS        | (1) Extrusion temperature = 265 °C  
(2) Bed temperature = 150 °C  
(3) Print speed = 40, 55, 70 mm/s  
(4) Layer thickness = 0.2, 0.3, 0.4 mm  
(5) Infill density = 20, 40, 60, 80, 100 % | 2.16    |
| M Sumalatha      | 2021  | Taguchi L9 orthogonal, ANOVA, S/N ratio | ABS Extrusion temperature = 230 °C | (1) Print speed = 40 mm/s  
(2) Layer thickness = 0.2, 0.3, 0.4 mm  
(3) Infill density = 25, 33, 50 %  
(4) Extrusion temp = 210 °C  
Infill density, print speed and extrusion temp less effect | 6.24    |
| Jasgurpreet Singh Chohan | 2022  | Taguchi L9 orthogonal, ANOVA, S/N ratio | ABS Layer thickness = 0.1 mm  
(1) Extrusion temperature = 210, 230, 250 °C  
(2) Print speed = 60, 70, 100 mm/s  
(3) Layer thickness = 0.10 mm  
(4) Extrusion temperature = 210 °C | 1.50    |
surface has a better surface finish compared to the side of the printed part. To reduce the overall surface roughness, printing the shortest part in the Z-direction is recommended. Furthermore, a low print speed and extrusion temperature are preferable to achieve good surface quality. In the work of Chohan et al. the authors reported that printing speed has a higher influencing factor with an 83.41% contribution on surface quality compared with the extrusion temperature (9.04%) [49]. The extrusion temperature should be set below its glass transition temperature. High extrusion temperatures cause the viscosity of filament materials to increase, i.e., they become more fluid, resulting in increased dimensional deviation and surface roughness. The raster angle and air gap have less impact on surface quality, as confirmed by Kumar et al. [50]. However, in contrast, there was a contractionary statement from Sukindar et al. who discovered that the raster angle has a significant influence on surface roughness [51]. A zero air gap is preferable to achieve good surface quality. Contour width did not have much influence on the surface finish on surface roughness.

To manufacture precise parts with critical dimensions, the surface roughness should be to equal or less than 0.8 μm. The surface roughness for FDM-printed parts without post-treatment ranges from 4 to 5 μm on average for Acrylonitrile Butadiene Styrene (ABS) and Polylactic acid (PLA). Based on a literature review, their maximum surface roughness for FDM-printed parts was 12 μm. Thus, for a surface quality enhancement in additive manufacturing, researchers have intensively explored various techniques for treatment. The roughness values recorded greatly decreased, with a reduction of up to 95% [52].

**Mechanical strength**

The strength of a printed product is defined as the ability to withstand the forces without deformation. Depending on the application areas, mechanical characteristics can be used as guidelines to explore new
application areas and determine the capability to replace the conventional parts or the expected service life of a part. The mechanical properties of FDM-printed parts are decreased compared with their raw filament material properties due to the heating-cooling process. In general, the mechanical properties of FDM-printed parts can be examined using ASTM standards. Table 2 shows a summary of research studies that have investigated the key parameters that influence the mechanical-related strength, including tensile, compression, flexural and impact strength. Tensile strength (ASTM D638), compressive strength and flexural strength (ASTM D790) were the three most widely analyzed mechanical properties of FDM parts. After the sample is fabricated, testing is carried out according to the standard process until the component ruptures and the load-strain relationship for each part is calculated. This relationship allows the determination and further analysis of the mechanical properties that are required for a specific application. The key parameters that can contribute to mechanical strength are discussed below:

**a. Effect of layer thickness on mechanical strength:** Tensile strength decreases with increasing layer thickness for both PLA and ABS filaments. Abbas et al. believed that the smallest layer thickness greatly enhanced the printed part strength because excellent interlayer bonding adhesion with less microvoids was generated at the smaller layer thickness\(^{[53]}\). Coogan et al. reported a large contact area (bonding width) for a low layer thickness that had an oval shape because of the wetting and better fusing of the filament [Figure 9]\(^{[54]}\). A higher elastic modulus and yield stress are observed for a lower layer thickness\(^{[55]}\). Some researchers have found that as the layer thickness increases, the tensile and flexural strength also increase\(^{[56,57]}\). The authors believed that a smaller number of layers is needed because they depend on the mechanical adhesion bonding between layers. Wu et al. reported that the tensile strength increased with layer thickness increments from 200 to 300 \(\mu\)m\(^{[58]}\); however, the strength was reduced at a layer thickness of 400 \(\mu\)m. This phenomenon occurred as a result of a weak interlayer caused by shrinkage and delamination of the welded layer, while residue stress was present among the stacking beads as a result of the temperature variation between the new molten layer and the previous solidified layer, resulting in strength degradation. While a smaller layer thickness is beneficial for tensile strength, this is not the case for compressive and impact loadings. The impact resistance and compressive strength of parts were found to have a direct relationship with the layer thickness.

Sharma et al. found that increasing the layer thickness from 0.1 to 0.3 mm resulted in an increase of the compressive stress from 33 to 42 MPa\(^{[59]}\). This was attributed to the fact that during the compression testing, a number of layers are prone to slide over each other due to shear stress causing the specimen to fail. For impact strength, which is defined as the ability of a material to absorb shock loads without breaking, greater bonding is required to absorb or transfer the stress between the microstructure of a layer. The impact resistance of the part decreased with a reduction in the layer thickness. This finding is in agreement with the results of Ramkumar et al. Hardness is defined as the ability to resist any deformation under concentration force and it decreases with each increment of layer thickness\(^{[60]}\). A high layer thickness produces a lower number of printed layers, which provides weaker bonder strength compared to the low layer thickness with a large number of printed layers. The temperature gradient in the initial layers increases as the number of layers increases. This causes the diffusion process between neighboring rasters to increase, thereby lowering the void ratio and strengthening the bonding. However, this can also lead to a greater number of heating and cooling cycles and can therefore increase the residual stress.

**b. Effect of infill density and pattern on mechanical strength:** The mechanical strength increases with the increment of infill density. This is due to more material having been deposited and hence the density increases with less hollow space inside the part, meaning more force is required to deform or change its original shape. The direct relationship was observed in previous studies for flexural and tensile strength and
Table 2. Summary of research studies investigating the influence of key parameters on mechanical strength in FDM printing

| First authors          | Year | Reference | Method                          | Mat. | Fix item                                                                  | Variable item                                                                 | Optimum                                                                 | Mechanical properties                |
|------------------------|------|-----------|---------------------------------|------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------|
| Sandeep Raut           | 2014 | [69]     | Direct experimental effect      | ABS  | (1) With support material (0.05 and 0.13 in²)                              | (1) Build orientation = X (0, 45, 90°); Y (0, 45, 90°); Z (0, 45, 90°);         | (1) Build orientation = X (0); good flexural strength and medium cost Y (0): good tensile strength and minimum cost | (1) Tensile strength = 33 - 35.45 MPa (2) Flexural strength = 28-45 MPa |
| Farzad Rayegani        | 2014 | [133]    | Full factorial, hybrid GMDH, and | ABS  | (1) Ambient temp = 23 °C                                                 | (1) Build orientation = 0, 90° (2) Raster angle = 0, 45° (3) Raster width = 0.2034, 0.5588 mm (4) Air gap = -0.0025, 0.5588 mm | (1) Build orientation = 0° (Lowest) (2) Raster angle = 50° (Highest) (3) Raster width = 0.2034 mm (Lowest) (4) Air gap = -0.0025 mm (Lowest) | (1) Tensile strength = 36.86 MPa |
| Wenzheng Wu            | 2015 | [58]     | Direct experimental effect      | PEEK and ABS | (1) Build orientation = Y direction (Flat) (2) Fill pattern = Line (3) Air gap = 0 (4) Number of contours = 2 (5) Nozzle diameter = 0.4 mm | (1) Layer thickness = 200, 300, 400 μm (2) Raster angle = 0/90, 30/60, 45/-45° | (1) Layer thickness = 300 mm (Medium) (2) Raster angle = 0/90° (Lowest) | (1) Tensile strength = 56.6 (2) Compression strength = 60.9 MPa (300 μm) |
| O.S. Carneiro          | 2015 | [76]     | Direct experimental effect      | PP   | (1) Extrusion temperature = 165 °C (2) Bed temperature = Room temperature (3) Print speed = 8 mm/s (1st layer), 60 mm/s (other layer) | (1) Infill density = 20, 60, 100% (2) Build orientation = 45, 0, 90°, crossed 45 ±45° and crossed 0-90° (3) Layer thickness = 0.20 and 0.35 mm | (1) Infill density = 100% (Highest) (2) Build orientation = ±45° (3) Layer thickness = 0.20 mm (Lowest) | (1) Young Modulus = 1000 MPa (2) Ultimate tensile strength = 20 MPa |
| Vijay.B. Nidagundi     | 2015 | [46]     | Taguchi’s L9 orthogonal array, Taguchi’s S/N ratio, ANOVA | ABS  | Not reported                                                              | (1) Layer thickness = 0.10, 0.20, 0.30 mm (2) Build orientation = 0, 15, 30 (3) Fill angle = 0, 30, 60 | (1) Layer thickness = 0.1 mm (Lowest) (2) Build orientation = 0 (Lowest) (3) Infill angle = 0 (Lowest) | (1) Ultimate tensile strength = 28.1 N/mm² (2) Dimensional accuracy = 0.3410 μm (3) Surface roughness = 0.3410 μm (4) Manufacturing time = 68 min (0.3 μm layer thickness) |
| Pritish Shubham        | 2016 | [134]    | Direct experimental effect      | ABS  | (1) Print speed = 15 mm/s Environment temp = 25 °C                        | (1) Layer thickness = 0.075, 0.10, 0.25, 0.50 mm | (1) Layer thickness = 0.075 mm (Lowest) | (1) Tensile strength = 27.5 MPa (Stress-strain curve) (2) Impact strength = 79.1 MPa |
| Z.Z. Abdullah          | 2017 | [78]     | Two-way ANOVA, Main effect plot | ABS and PLA | (1) Build orientation = Flat (2) Air gap = Level 1 (3) Fill density/pattern = 30%, Rectilinear | (1) Layer thickness = 0.20, 0.30, 0.40 mm (2) Raster angle = 30/60, 45/-45° (3) Layer thickness = 0.4 mm (PLA); 0.3 mm (ABS) (2) Raster angle = 30°/60° (PLA); 45°/-45° (ABS) | (1) Layer thickness = 0.4 mm (PLA); 0.3 mm (ABS) (2) Raster angle = 30°/60° (PLA); 45°/-45° (ABS) | (1) Tensile strength = 33 MPa (PLA); 24 MPa (ABS) (2) Flexural strength = 49 MPa (PLA); 35 MPa (ABS) |
| Name                     | Year     | Method                          | Material | Parameters                                                                 | Results                                                                 |
|--------------------------|----------|---------------------------------|----------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------|
| J.M. Chacón              | 2017     | ANOVA analysis, regression      | PLA      | (1) Air gap = 0 mm (2) Raster angle = 0° (3) Extrusion temp = 210 °C        | (1) Build orientation = Flat (F), On-edge (O), Upright (U) (2) Layer thickness = 0.06 (3) Extrusion speed rate = 20, 50, 80 mm/s |
|                          |          | models and response surfaces    |          |                                                                             |                                                                         |
| Taheen Tahseen Fadhil Abbas | 2018     | Direct experimental effect      | PLA      | (1) Print speed = 100 mm/s (2) Infill density = 80% (3) Build orientation= 45° | (1) Layer thickness = 0.10, 0.15, 0.20, 0.25, 0.30 mm                  |
|                          |          |                                 |          |                                                                             |                                                                         |
| Vladimir E. Kuznetsov    | 2018     | Direct experimental effect      | PLA      | (1) Print speed = 25 mm/s                                                  | (1) Nozzle diameter = 0.40, 0.60, 0.80 mm (2) Layer thickness = 0.06- 0.60 mm |
|                          |          |                                 |          |                                                                             |                                                                         |
| Claire Benwood           | 2018     | Direct experimental effect      | PLA      | (1) Print speed = 50 mm/s (2) Infill density = 100% (3) Print time = 6.5 hours | (1) Bed temp = 45, 60, 75, 90, 105 °C (2) Extrusion temp = 190, 200,210, 220, 230 °C |
|                          |          |                                 |          |                                                                             |                                                                         |
| Martin Spoerk            | 2018     | Direct experimental effect      | PLA and ABS | (1) Print speed = 50 mm/min (2) Filament diameter = 1.75 mm                | (1) Bed temperature= 30-120 °C (2) Bed material = Glass, PL (1) Bed temp = 70 °C (PLA); 120 °C (ABS) |
|                          |          |                                 |          |                                                                             |                                                                         |
| K.G. Jaya Christiyan     | 2018     | ANOVA (quadratic model),       | PLA      | (1) Fill pattern = -45/45 (2) Extrusion temperature = 180 °C (3) Bed temperature = 40 °C (4) Infill percentage = 70% | (1) Nozzle diameter = 0.40, 0.50, 0.60 mm (2) Layer thickness = 0.20, 0.25, 0.30 mm |
|                          |          | Normal Probability plot, Contour plot, Response surface graph |          |                                                                             |                                                                         |
| Łukasz Miazio            | 2019     | Statistical analysis           | PLA      | (1) Extrusion temperature = 215 °C (2) Layer thickness = 0.2 mm (3) Fill density = 30% | (1) Print speed = 20, 30, 40, 50, 60, 70, 80, 90, 100 mm/s |
|                          |          |                                 |          |                                                                             | (1) Print speed = 50-80 mm/s                                             |
|                          |          |                                 |          |                                                                             | (1) Breaking force = 0.55 kN                                             |
| Ding                     | 2019     | Direct experimental effect      | PEEK and PEI | (1) Bed temperature = 270 (PEEK), 210 (PEI) (2) Layer thickness = 0.2 mm (3) Print speed = 20 mm/s | (1) Extrusion temperature = 360, 370, 380, 390, 400, 410, 420 (2) Build orientation = Vertical, Horizontal |
|                          |          |                                 |          |                                                                             | (1) Extrusion temperature = 390-400 °C for PEEK; 420 °C for PEI (2) Build orientation = Horizontal |
|                          |          |                                 |          |                                                                             |                                                                         |
| Vinaykumar S Jatti       | 2019     | Direct experimental effect      | PLA      | (1) Nozzle diameter = 0.4 mm                                                | (1) Tensile strength = 58 N/mm² (Infill density = 100%, Print speed = 50 mm/s, Layer thickness = 0.16 mm, Extrusion temp = 220 °C) |
|                          |          |                                 |          |                                                                             | (2) Impact strength = 3.5                                                |
impact resistance\(^{[60-62]}\). Vicente \textit{et al.} reported that the tensile strength for the ABS-printed product increased from 700 to 720 MPa when the infill percent was increased from 95\% to 105\% (negative airgap)\(^{[63]}\). Apart from the infill density, the infill pattern also plays a role in the enhancement of the mechanical properties of the printed part as it influences the interaction between infilled filaments with one another. Alayoldi \textit{et al.} reported no significant difference in
tensile strength between triangular (66.3 MPa), grid (72.0 MPa) and hexagonal (58.8 MPa) infilled patterns\cite{64}; however, the quarter cubic exhibited a lower strength of 27.4 MPa. This is due to the grid pattern having a special layer arrangement where the layers crisscross above each other, while the quarter cubic pattern has an offset between the layers [Figure 10].

\textbf{c. Effect of build orientation on mechanical strength:} In terms of the tensile strength of FDM-printed parts, most research shows that lower values (0°) of build orientation are best, whereas the flexural and impact strength properties show varied optimal orientations. However, it is subject to the direction of the load applied and the material properties\cite{65}. Abdelrhman \textit{et al.} reported a maximum tensile strength of 29.36 MPa and fracture load of 1409.09 N using an XY build orientation\cite{66}. Eryildiz \textit{et al.} reported 36\% less tensile strength for an upright orientation (35.52 MPa) compared to the flat 0° orientation (55.49 MPa) because of the fracture mode and loading direction\cite{67}. The interlayer fracture strength mainly depends on the interlayer bonding strength, while the intralayer fracture mainly depends on the strength of the extruded material\cite{68}. Vishwas \textit{et al.} found that the tensile strength was maximized for ABS-printed parts (26.41 MPa) using a 15° orientation and using a 30° build orientation for nylon (25.48 MPa)\cite{69}. Raut \textit{et al.} reported that the lowest build orientation is optimal for the tensile strength of ABS parts (35.45 MPa at x axes|22.51 MPa at y axes|33.00 MPa at z axes)\cite{70}. In the case of the flexural strength, the higher build orientation levels resulted in better flexural strength values, excluding the x axis. The maximum flexural strength of 45.20 MPa was noted using the 0° build orientation with respect to the x axis. The illustration of the relationship between the tensile and flexural strength of ABS parts and different build orientation levels with respect to the x, y and z axes is shown in Figure 11B.

\textbf{d. Effect of print speed on mechanical strength:} Some researchers have highlighted that print speed has a significant influence on mechanical strength\cite{71}, while others have reported that it is almost unaffected. As a result, strength is determined by layer-to-layer adhesion. Miazio \textit{et al.} investigated the relationship between print speed, which varied from 20 to 100 mm/s, with tensile strength\cite{72}. The authors reported no significant difference for the print speed range of 50-80 mm/s; however, after 80 mm/s, the strength was decreased. This is caused by the limited capacity of the print head. The time needed to plasticize the filament is too short. In turn, the printing time exponentially increases with a decrease in speed. For high speed printing, less material is deposited, leading to void formation that reduces the overall strength of the printed part.

\textbf{e. Effect of extrusion temperature on mechanical strength:} The strength-extrusion temperature relationship is not linear. Tensile and flexural strength increase with extrusion temperature until they reach a maximum value and start to deteriorate when exceeding the glass transition temperature. When an extrusion
temperature is below the filament material’s glass transition temperature, the new layer fuses with the extruded layer and interlayer bonding is generated. High extrusion temperatures above the glass transition temperature provide strong interlayer bonding between layers and the oval bead shape is created, resulting in an increment of strength. However, some researchers believe that as the temperature increases\cite{72}, the viscosity of the filament material reduces, resulting in a reduction in the overall thickness of the part that can lead to strength degradation. The material also tends to undergo degradation\cite{73} and becomes more brittle at high temperatures [Figure 12]\cite{74}. In order to increase the bonding between layers, the diffusion time, which refers to the time taken for the material to cool down to its glass transition temperature, should be increased. Zhou et al. concluded that an increase in extrusion and bed temperature extends the diffusion time, resulting in increased bond strength and overall mechanical properties\cite{75}.

f. Effect of raster related parameter on mechanical strength: It was reported that the minimum level (0°) of raster angle improves the tensile and flexural strength of FDM parts, while the impact strength can be improved using a 45°/-45° (staggered raster) raster angle. In fact, the strength relies on the direction of the load applied\cite{76} as the molecules tend to align along the stress axis direction. The tensile strength decreases as the raster angle increases. 0° raster angle is the optimal level in terms of tensile strength along with a 0.1 mm layer thickness and 0° part orientation. This is because tensile strength depends on the alignment between
the axis where the stress is applied. Therefore, increasing the raster angle results in a misalignment between two axes causing weaker parts in terms of tensile strength. In the case of a PLA resin, Liu et al. found that the raster angle of $0^\circ$ is optimal and results in the highest tensile and flexural strength\cite{77}. The authors studied three levels of raster angle, namely, long-raster ($0^\circ$), long-short-raster ($+90^\circ/0^\circ$) and staggered-raster ($+45^\circ/-45^\circ$). The long-short-raster means a layer with a $90^\circ$ raster angle is followed by a consecutive layer with a $0^\circ$ raster angle during the printing process. Based on the results of ANOVA analysis that demonstrates the percentage contribution of parameters, it was found that the raster angle parameter mostly affects the impact strength (0.127%) of PLA parts compared to tensile (0.002%) and flexural strength (0.034%). The optimal level in terms of the impact strength was found to be staggered-raster ($+45^\circ/-45^\circ$).

\section{Short discussion and summary of key parameters related to mechanical strength:} For tensile properties, the build orientation and layer thickness were found to be the most significant parameters in achieving maximum tensile strength. Lower values ($0^\circ$) of build orientation and layer thickness are recommended for tensile strength. According to Abdullah et al. layer thickness and raster angle have a significant impact on tensile strength in isolation but not in combination\cite{78}. Although the optimum raster orientation for tensile strength is still contradictory, it may be concluded that a $0^\circ/90^\circ$ or $-45^\circ/45^\circ$ raster orientation is optimum. Rao et al. reported that the extrusion temperature and infill pattern contributed 7.95% and 3.93% to tensile strength in their study\cite{79}. Tensile strength increases in a non-linear relationship with extrusion temperature, whereas it increases until it reaches maximum value and begins to deteriorate. High extrusion temperature
and below the glass transition temperature is preferable for tensile strength. However, extrusion temperatures did not have a significant influence as a printing speed parameter. The recommended print speed range is \(~45-50\) mm/s. The tensile strength is maximized at a high infill percentage and an infill pattern that has a layer arrangement that is crisscrossed with good intralayer bond connection.

For compressive properties, according to the state-of-art research, there are still very limited studies that investigate their relationship with process parameters that have been carried out. In our opinion, we believe further investigation is required to reach a solid conclusion on the process parameter relationship with compressive strength. For flexural properties, their relationship is more complex compared to tensile and compression strength as it involves both forces. The build orientation and layer thickness were found to be the most significant influence parameters on flexural strength. A \(0^\circ\) build orientation and low layer thickness are the optimum conditions to obtain the maximum flexural strength. According to Christiyan et al., the layer thickness influence was 36.61%, followed by nozzle diameter (27.45%) and print speed (5.39%) on flexural strength\[^{[80]}\]. A high extrusion temperature is recommended to increase the flexural strength. Based on the current literature review, very little research has been conducted on other process parameters, such as the infill pattern and density, print speed and raster angle. It would be beneficial for public knowledge if researchers could explore more parameters to be analyzed concurrently to determine the influence of printed components on flexural strength as one of the future research directions.

Based on a literature review, the FDM-printed part of PEEK has superior properties, including tensile and flexural strength. The greatest tensile strength ranged from 56 to 95 MPa, followed by PLA (33-87 MPa), nylon (46.2 MPa), ABS (24-56.6 MPa) and PP (20 MPa). The highest flexural strength of 135 MPa was followed by PEI (123 MPa), PLA (49-110 MPa) and ABS (35-45 MPa). The mechanical properties after printing are decreased compared with their material properties in raw filament form and the comparison among various materials for before and after FDM printing is shown in Figure 13. The mechanical properties that should be targeted based on their application. Despite this, there is very little information available on the minimum value of mechanical properties that were required. From the existing research, it can be initially concluded that the intended tensile strength was \(\geq 40\) MPa\[^{[81]}\] and the flexural strength was \(\geq 214\) MPa\[^{[82]}\] to produce printed parts that dealt with heavy loads, such as load bearing. The intended compression strength was \(\geq 24\) MPa and the flexural strength was \(\geq 45\) MPa for products that did not deal with heavy loads.

**Dimensional accuracy**

Accuracy is defined as the difference\[^{[83]}\] between the dimensions of a printed product and a virtual CAD model, which may differ due to material shrinkage\[^{[84]}\] during the phase transition\[^{[85]}\] or material expansion due to imperfect first layer adhesion\[^{[86]}\] caused by the thermal gradient, resulting in warping. In this section, the key parameters that can influence the dimensional accuracy of the printed parts are summarized systematically in Table 3 and detailed explanations for each parameter are presented as follows:

**a. Effect of layer thickness on dimensional accuracy:** Thermoplastic materials have the issue of shrinkage when dealing with high and low temperatures. The dimensional accuracy is optimum for low layer thicknesses. However, there is a contradiction in this statement based on the findings of Sood et al. who recommended a high layer thickness as the optimum condition for dimensional accuracy\[^{[87]}\]. This conflict can be narrowed down to the type of material as Sood et al. used PLA while Nancharaiah et al. and Milde et al. used ABS for their studies\[^{[87-89]}\]. ABS has a higher shrinkage rate compared to PLA. Material dependency is a considerable condition of the optimal layer thickness for selection that might affect dimensional accuracy. Basically, the nozzle extrudes the material onto a platform in an elliptical bead shape,
Table 3. Summary of research studies investigating the influence of key parameters on dimensional accuracy in FDM printing

| First authors | Year | Reference | Methodology | Material used | Fix parameter | Variable item | Optimum value | Dimensional accuracy |
|---------------|------|-----------|-------------|--------------|---------------|---------------|---------------|---------------------|
| Vijay. B. Nidagundi | 2015 | [46] | Taguchi L9 orthogonal array, Taguchi’s S/N ratio, ANOVA | ABS | Not reported | (1) Layer thickness = 0.10, 0.20, 0.30 mm (2) Build orientation = 0, 15, 30 (3) Fill angle = 0, 30, 60 | (1) Layer thickness = 0.10 mm (Lowest) (2) Build orientation = 0 (Lowest) (3) Fill angle = 0 (Lowest) | Dimensional for printed model (1036.05 mm³) bigger than CAD model (1000 mm³) |
| Stephen O. Akande | 2015 | [122] | Factorial design, Pareto chart, DFA | PLA | Not reported | (1) Layer thickness = 0.25, 0.50 mm (2) Print speed = 16, 21.33 mm/s (3) Infill density = 20%, 100% | (1) Layer thickness = 0.25 mm (Lowest) (2) Print speed = 16 mm/s (Lowest) (3) Infill density = 20% (Lowest) | The thickness dimension was the most inaccurate |
| Young-Hyu Choi | 2016 | [96] | Direct experimental effect | ABS | Not reported | (1) Nozzle diameter = 0.8 mm (2) Extrusion temperature = 240 °C (3) Print speed = 50 mm/s (4) Layer height = 0.30 mm | (1) Bed temp = 40, 50, 70, 90, 110 °C (Highest) | Heat shrinkage shape error (%) failed in AM at bed temp 40 °C |
| Ján Milde | 2017 | [89] | Arithmetical means | ABS | Not reported | (1) Layer thickness = 90, 190, 290 μm | (1) Layer thickness = 0.09 mm (Lowest) | Arithmetical mean deviation of -0.25 mm for 0.09 mm layer thickness |
| Saroj Kumar Padhi | 2017 | [102] | Taguchi L27 orthogonal array, fuzzy inference | ABS | Not reported | (1) Layer thickness = 0.127, 0.178, 0.254 mm (2) Build orientation = 0, 15, 30 (3) Raster angle = 0, 30, 60 (4) Raster width = 0.406, 0.456, 0.506 mm (5) Air gap = 0, 0.004, 0.008 mm | (1) Layer thickness = 0.178 mm (Medium) (2) Build orientation = 0° (Lowest) (3) Raster angle = 0° (Lowest) (4) Raster width = 0.4564 mm (Medium) (5) Air gap = 0.008 mm (Highest) | Layer thickness major contribution individually on L and T. |
| Ala’aldin Alafaghani | 2017 | [57] | Direct experimental effect | PLA | Not reported | (1) Build orientation = X, Y, Z (2) Infill density = 20, 50, 80% (3) Print speed = 70, 120, 170 mm/s (4) Extrusion temp = 175, 180, 205 °C (5) Layer thickness = 0.10, 0.25, 0.40 mm (6) Infill | (1) Build orientation = Z (2) Infill density = 50% (Medium) (3) Print speed = 90 mm/s (4) Extrusion temp = 185 °C (5) Layer thickness = 0.25 mm (Medium) (6) Infill pattern = Diamond F | The length of printed part smaller than model, while width and thickness dimensions increase |
| Study                                      | Methodology                          | Material | Parameters                                                                 | Result                                                                 |
|--------------------------------------------|--------------------------------------|----------|---------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Vishwas M 2018 [68]                        | Taguchi Orthogonal Array              | ABS      | (1) Nozzle diameter = 0.40 mm, (2) Filament diameter = 1.75 mm            | Dimensional for printed model (1007 mm³) slightly bigger than CAD model (1000 mm³) |
|                                            |                                      |          | (1) Layer thickness = 0.30 mm, (2) Build orientation = 15, 30             |                                                        |
|                                            |                                      |          | (3) Shell thickness = 0.4, 0.8, 1.2 mm                                    |                                                        |
|                                            |                                      |          | (1) Extrusion temp = 245, 255, 265 °C, (2) Print speed = 50, 60, 70 mm/s |                                                        |
|                                            |                                      |          | (3) Layer thickness = 0.10, 0.15, 0.20 mm                                 |                                                        |
|                                            |                                      |          | (1) Extrusion temp = 255 °C, (2) Print speed = 60 mm/s, (3) Layer thickness = 0.15 |                                                        |
|                                            |                                      |          | (1) Layer thickness = 0.30 mm, (2) Build orientation = 15                |                                                        |
|                                            |                                      |          | (3) Shell thickness = 0.4 mm                                             |                                                        |
|                                            |                                      |          | (1) Layer thickness = 0.25 mm, (2) Extrusion temp = 235 °C, (3) Print speed = 55 mm/s |                                                        |
|                                            |                                      |          | (4) Infill density = 20, 25, 30                                           |                                                        |
|                                            |                                      |          | (5) Bed temp = 90, 95, 100 °C                                            |                                                        |
|                                            |                                      |          | (1) Layer thickness = 0.4 mm (Highest), (2) Infill density = 100%         |                                                        |
|                                            |                                      |          | (3) Bed temp = 100 °C (Highest)                                          |                                                        |
|                                            |                                      |          | (1) Infill density = 20, 50, 100%                                         |                                                        |
|                                            |                                      |          | (2) Layer thickness = 0.10, 0.15, 0.20 mm                                 |                                                        |
| Aissa Ouballouch 2019 [145]                | Direct experimental effect            | GRPA; KRPA| (1) Build orientation = 45°                                              | Dimensional accuracy of KRPA is more affected by the printing parameters than GRPA |
|                                            |                                      |          | (1) Extrusion temp = 245, 255, 265 °C                                     |                                                        |
|                                            |                                      |          | (2) Print speed = 50, 60, 70 mm/s                                         |                                                        |
|                                            |                                      |          | (3) Layer thickness = 0.10, 0.15, 0.20 mm                                 |                                                        |
| OM F Marwah 2019 [103]                     | Fractional factorial design (ANOVA, Pareto chart, Main Effects Plot) | ABS      | (1) Layer thickness = 0.20, 0.25, 0.30 mm                                 | Different between CAD and printed model is 2.56%                         |
|                                            |                                      |          | (2) Extrusion temp = 230, 235, 240 °C                                     |                                                        |
|                                            |                                      |          | (3) Print speed = 50, 55, 60 mm/s                                         |                                                        |
|                                            |                                      |          | (4) Infill density = 20, 25, 30                                           |                                                        |
|                                            |                                      |          | (5) Bed temp = 90, 95, 100 °C                                            |                                                        |
|                                            |                                      |          | (1) Layer thickness = 0.25 mm, (2) Extrusion temp = 235 °C, (3) Print speed = 55 mm/s |                                                        |
|                                            |                                      |          | (4) Infill density = 25%                                                  |                                                        |
|                                            |                                      |          | (5) Bed temp = 100 °C                                                     |                                                        |
| Elizabeth Azhikannickal 2019 [146]         | RMS (root mean square) error          | ABS      | (1) Extrusion temp = 230 °C                                               | Printed model not adhere to the print bed and the molten plastic at layer thickness ≥ 0.4 mm. No significant different on infill relationship with dimensional accuracy |
|                                            |                                      |          | (1) Layer thickness = 0.10, 0.20, 0.34, 0.40 mm                            |                                                        |
|                                            |                                      |          | (2) Infill density = 20, 50, 100%                                         |                                                        |
| Amirah Azwani Rosli 2020 [99]              | Direct experimental effect            | ABS      | (1) Extrusion temp = 240 °C                                               | Warpage decreased with increasing bed temperature; thick sample indicated lower shrinkage |
|                                            |                                      |          | (1) Bed temp = 90, 100, 110 °C                                           |                                                        |
|                                            |                                      |          | (1) Bed temp = 110 °C (Highest)                                          |                                                        |
| Ahmed Elkaseer 2020 [93]                   | Taguchi L50 orthogonal array          | PLA      | (1) Bed temp = 60 °C                                                     | Thin layers and high printing speeds reduce percentage error |
which has an uneven surface. The next deposition will be stacked on the uneven previous layer, leading to dimensional variation, especially on the Z axis. Consideration of tolerance to compensate for shrinkage by scaling when printing is highly recommended in order to provide the ability to print the feature in the desired range of tolerance [90, 91].

b. Effect of build orientation on dimensional accuracy: Deposition orientation in the Z-direction is the most significant parameter for dimensional accuracy. However, it is difficult to explain how building orientation can have an effect on dimensional accuracy. What is certain is that it clearly contributes to dimensional accuracy. There is the potential for printers to have differences in positional resolution. Attribution from gravity effects as it relates to a semi-liquid or liquid also has potential in this case. The 45° angle specimens had the lowest dimensional accuracy. This is because, due to layer positioning, there are expected to be layers of printed parts built tilted. As a result, the risk of distortion increases due to the gravity impact throughout curing [92].

c. Effect of extrusion temperature on dimensional accuracy: Depending on the printing material, it is important to set the extrusion temperature to the correct value. Too high extrusion temperatures (above the glass transition temperature) can degrade the surface quality. This might be explained by the increased extrusion temperature reducing the viscosity of the melted filament [93]. In other words, it will increase the fluidity of the extruded material, thereby allowing it to flow fast and out of control, thus contributing to
dimensional inaccuracy. This statement is agreed upon by most researchers\[94,95\].

d. Effect of bed temperature on dimensional accuracy: Warpage and shrinkage can be reduced with increasing bed temperature. Large differences between the extrusion and bed temperatures can cause a reduction in the ability to release the thermal stress and thus the heat shrinkage increases. Choi et al. highlighted that the bed temperature needs to be set as close as possible to the softening temperature of the filament material in order to compromise with a reduction in its heat shrinkage\[96\]. The lower shrinkage observed in the thick printed sample than the thin printed sample as thick printed sample might have a greater volume with a longer conduction path that causes a lower cooling rate that induces less thermal contraction\[97\]. Furthermore, it allows the printed part to not stick to the platform, which might generate the sticking mark and effect their dimensions\[98\].

e. Effect of infill density on dimensional accuracy: The infill density reflects the amount of filament material printed inside the object. The relationship between infill density and dimensional accuracy is not stated explicitly. The building parts need layers to support each other in order to reduce the potential for object collapse. Increased infill density allows for better dimensional control. In addition, the infill density determination also depends on the size of the printed parts. Due to the nature of the behavior of polymers that expand and shrink when dealing with heat, increased infill density increases the "fullness" amount of material inside the printed part, which means less space for them to expand or shrink, which has an effect on the dimensional accuracy. Rosli et al. highlighted that high-volume products (large size) have a low cooling rate, which causes less thermal contraction and contributes to lower shrinkage\[99\].

f. Effect of print speed on dimensional accuracy: In order to improve the dimensional accuracy, the print speed should be decreased. At high print speed, less material extrusion and time to connect the new molten state layer to the solidified layer reduce the dimensional accuracy. An unexpected result was observed in Agarwal et al. who found that the low print speed has higher dimensional deviation compared to the high print speed\[100\]. This is explained that once the shear rate exceeds a critical value, an increase in shear rate decreases the extrudate swell. In other words, higher print speeds increase the shear rate beyond a critical value after which the melted material on deposition does not flow.

g. Effect of air gap on dimensional accuracy: A positive or negative air gap spacing bring diffusion of the material between bead generate issue on dimensional tolerance because of over/underfilling at the contact area, which results in an uneven layer. As a result, the following layer deposited stacking on top of this uneven layer will not have an even planer surface, which might result in a dimension increase along the part construction direction\[101\].

h. Short discussion and summary of key parameters related to dimensional accuracy: The layer thickness is one of the most studied and significant parameters for dimensional accuracy according to the presented literature review. The setting of the optimum layer thickness is based on the material used to reflect the expansion-shrinkage rate once it has been dealt with heat. In contrast, a low layer thickness is recommended for easier dimension control. Nidagundi et al. highlighted that layer thickness has the greatest impact on the dimensional accuracy (75.52%), followed by build orientation (13.11%) and raster angle (11.67%)\[46\]. The same finding was found by Sood et al. Vishwas et al. highlighted that layer thickness gives the major contribution to dimensional accuracy (84.84%), followed by contour width or shell thickness (12.66%) and build orientation (2.5%)\[68,87\]. Sood et al. reported that layer thickness contributes 10.68%, 42.87% and 83.19% of the dimensional variation of the length ($\Delta L$), width ($\Delta W$) and thickness ($\Delta T$), respectively\[87\]. Padhi et al. reported that layer thickness plays the main role in the dimensional variation of
ΔL and ΔT with 44.44% and 83.17%, respectively, while for ΔW dimensional accuracy, the main contributor parameter is build orientation (23.91%)\(^{102}\). Shrinkage was commonly noticed along the X and Y axes of build platforms, whereas expansion was observed along the Z axis of the build platform.

Marwah et al. disagreed that layer thickness is the main parameter that contributes to dimensional error\(^{103}\). They stated that the bed temperature has a greater influence on shrinkage than layer thickness, which was supported by ANOVA studies with a $P$-value of 0.000 when compared to the other four factors, which were layer thickness ($P$-value of 0.156), extrusion temperature ($P$-value of 0.595), print speed ($P$-value of 0.152) and infill density ($P$-value of 0.089). It is critical to adjust the extrusion temperature to the right value depending on the printing material. The authors highlighted that infill density is the highest impact parameter after extrusion temperature. Suaidi et al. reported that build orientation contributes 22.91%, layer thickness contributes 9.97% and infill density is 46.12%\(^{104}\). The significance of infill density was also found by Robles et al.\(^{105}\). Increased infill density allows for better dimensional control. However, the infill density finding conflicts with Alafaghani et al. finding as the authors highlighted that infill density and pattern have no or very little influence on the dimensional error\(^{57}\). In order to improve the dimensional accuracy, print speed should be decreased. According to their ANOVA analysis, Baraheni et al. reported that print speed has a significant effect on the dimensional error with a 43.92% contribution\(^{106}\). A zero air gap is recommended for minimal dimensional error.

However, in our perspective, further analysis is needed regarding the layer thickness, extrusion temperature, infill density, print speed and air gap for validation of the conclusion. The effects of many process parameters, including raster angle, raster width, number of shells and shell thickness, on dimensional accuracy are still unknown. To build a product with great dimensional precision, it is critical to understand the impact of these parameters. The need to have a very accurate dimensional printed part as close as possible to the original design is highly important as it will influence how well the product will be accepted and approved for distribution to the end users. Most research has focused on only two or three layers of parameters. It is highly recommended to analyze more than three levels of parameters and explore the effect of known parameters on dimensional accuracy in order to visualize their relationship, thereby leading to more accurate decisions. FDM printing should have a dimensional tolerance of ±0.15% and a lower limit of ±0.2 mm. A tolerance of more than +/-0.5 mm is considered poor dimensional accuracy.

Based on the presented literature review, Figure 14 shows a summary of the fish-bone cause analysis, which consists of various FDM process parameters that influence the corresponding printed product characteristics (surface roughness, mechanical strength and dimensional accuracy) and their contribution rate. A simple summary of the relationship between the FDM process parameters and their output is depicted in Table 4 to better understand and identify the research gap in the key areas.

**CHALLENGES**

According to numerous research studies, it has been clearly identified that there are a few drawbacks that directly affect the part characteristics in FDM printed polymers that cannot be rectified solely by using the optimal printing conditions. Several significant challenges remain unresolved, which contribute to the part characteristics, including surface roughness, mechanical strength and dimensional accuracy. These are residual stresses caused by non-uniform temperature gradients, the existence of voids and the staircase effect.

**a. Non-uniform heating and cooling cycles:** In FDM, the internal stress increases in the printed part during the printing process due to rapid heating and cooling cycles, causing non-uniform temperature gradients
Table 4. Effect of design, process and material parameters for printed polymeric product

| Aspect | Relationship effect | Surface roughness | Mechanical strength | Dimensional accuracy |
|--------|---------------------|-------------------|--------------------|---------------------|
|        |                     |                   | Tensile strength   | Flexural strength   |
|        | Increment of key parameter |                  |                    |                     |
| Factor | Process perspective | Layer thickness   | ▲ △                 | ▲                   |
|        |                     | Infill density    | ▲ ▲ ▲ ▲             | ▲ ▲ ▲ ▲             |
|        |                     | Air gap           | ▼ ▼                 | ▼ ▼                 |
|        |                     | Raster width      | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |
|        |                     | Raster angle      | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |
|        |                     | Build orientation | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |
|        |                     | Print speed       | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |
|        |                     | Extrusion temp    | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |
|        |                     | Bed temp          | ▼ ▼ ▲ ▲             | ▼ ▼ ▲ ▲             |

Definition: ▲ = increase; ▼ = decrease; ▲▼ = increase then decrease; *other parameter dependent

Figure 14. Cause analysis via a fish-bone diagram and contribution rate.

that lead to shape distortion, dimensional inaccuracy and inner layer cracking or delamination\textsuperscript{[107]}. Non-uniform heating and cooling cycles are attributed to a number of factors, as follows: (1) conduction and forced convection release heat and the resulting drop in temperature, which drives the material to solidify fast onto the surrounding filaments. When the new extruded material is deposited on the previously solidified material and diffused in order to ensure the bonding is performed, a local re-melting is generated. This phenomenon leads to uneven heating and cooling and non-uniform temperature gradients being produced\textsuperscript{[108]}. Thus, as a result, uneven stress affects the shape and dimensions of the printed part. Shrinkage, bucking, twisting and warpage are all examples of distortion defects that might be caused by this phenomenon, which involves the part lifting up and being unable to be placed properly on the printing platform; (2) the temperature gradient within a nozzle during the printing process has a significant effect on the print speed. The rate and amount of deposition material might affect the heating and cooling cycle, resulting in a different degree of thermal gradient on the printed part. The print speed is lower (faster) at lower layer thicknesses than at larger layer thicknesses. Shape distortion may be reduced by using the right
nozzle temperature, printing at a slower speed, and using a low layer thickness; (3) the design and size of the printed part have a significant effect on the thermal distribution, resulting in different stress and deformation behavior. At the bottom of the surface and each layer of printed part, the long raster tool-path exhibits a higher stress concentration pattern, and as each layer progresses, the stress accumulates at the initial deposition positions. To reduce tension, a short raster length is preferable along the long axis of the component; (4) high layer thickness, which means having a lesser number of layers, could reduce the accumulation of residual stress by reducing the number of heating and cooling cycles compared to the low layer thickness.

**b. Existence of voids:** A void is a small cavity that forms between the layers of a printed part. These voids weaken the part and make it prone to mechanical failure. They can cause delamination and the formation of porosity between subsequent layers, resulting in anisotropic characteristics. Stress concentrations formed at voids reduce part performance. Partial neck growth voids are a significant contributor to the occurrence of voids in FDM. The partial neck growth void occurs when there is incomplete neck growth between adjacent beads during the sintering process. It is difficult to sustain neck growth with 100% coalescence between two adjacent beads. Problems with solidification before complete coalescence may be caused by inherent characteristics, such as partial filling and inconsistent material flow. The incomplete filling of the area inside the perimeter of the FDM part causes sub-perimeter voids. The travel direction of the extruder changes to a route that is tangent to the perimeter as the path approaches the perimeter. Thus, incomplete material flow for filling, which required sharper U-turns at these intersections, leads to void formation. Giving the perimeter a negative offset and/or raising the flow rate at the points of intersection are two methods for fixing this problem. However, adjusting the process parameters should be done carefully to avoid the creation of new defects.

**c. Staircase effect:** To reduce surface roughness, we might use a low layer thickness. However, regardless of the low layer thickness, the inclined surface of FDM parts will always have a stair-stepping effect and the horizontal surface will always have a raster pattern. These visible rough patterns cannot be avoided, but surface finishing can be improved by using the best post-processing techniques. Surface quality improvement strategies are divided into two categories: mechanical and chemical. Some of the mechanical approach post-processing methods are manual sanding, gap filling, abrasive flow machining, abrasive milling, hot cutter machining, ball burnishing and vibratory finishing. Example of chemical approaches are coating, acetone dipping and vapor smoothing. The manual post-processing method may become an issue in terms of labor costs and time, both of which are considerable on larger production volumes. The development of automated post-processing equipment by printer makers would help the industry expand its scope of applications and acceptance of additive manufacturing. There are numerous research studies focused on post processing for improving the surface quality of FDM parts. They have discussed and assessed the best condition of post-processing techniques for improving the surface finish.

**CONCLUSION AND FUTURE PERSPECTIVE**

We are moving forward from a multi-step process to a single-step process with low-cost, low material wastage, high productivity and less production time. In this review, a list of process parameters with their definition, factors and effects on the characteristics of FDM-printed products, such as surface roughness, mechanical strength and dimensional accuracy, is presented. Layer thickness is the most influential factor on printed product quality among all FDM process parameters. There are still many unexplored factors that need further analysis. However, the study scope is limited to standard nozzle size and available software that attributes certain parameters such as layer thickness, raster width and number of outer shells. This constraint makes the optimization of variable process parameters more complex and needs to be overcome.
by developing optimization techniques using statistical tools. Although numerous designs of experiments have been carried out to identify the relationships among parameters in terms of individual or combination parameter optimization studies for a single output variable, there are variations in the result findings. What is certain is that actual physical output differs from the prediction of optimization techniques. In the future, researchers must focus on multi-objective optimization to see concurrent relationships in multiple output variables. Hence, newer approaches to mathematical modeling might be required to synchronize and minimize the variation of the result. To achieve full acceptance, optimization must focus on meeting manufacturing requirements for reproducibility, reliability, precision, productivity, efficiency, manufacturing cost and balancing without jeopardizing one another. A clear and comprehensive understanding of their interrelations is necessary.

DECLARATIONS

Authors’ contributions
Conceptualization, methodology, formal analysis, investigation, data curation, writing - original Draft: Ahmad NN
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Conceptualization, validation, resources, review & editing, visualization, supervision, project administration, funding acquisition: Wong YH

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All authors declared that there are no conflicts of interest.

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Not applicable.

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