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Effects of Common FDM Printing Parameter on Tensile Strength and Material Consumption: A short review

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Abstract: Fused deposition modelling (FDM), a form of additive manufacturing (AM) is a process that constructs product similar to that of material extrusion is a radically growing modern manufacturing approach that efficiently reduces cycle time during product development with minimal losses. Despite the minimal losses, developing FDM products with high mechanical strength entails high material consumption and longer print time making it cost inefficient. Therefore, this paper reviews several existing works to identify common printing parameters significant to improving tensile strength and material consumption of FDM printed products. Additionally, it is expected that isolating these significant parameters could benefit future research by providing direction for possible printing parameter optimization.

Keywords: fused deposition modeling; process parameters; tensile strength; material consumption

INTRODUCTION

Recently, FDM has been widely preferred over other conventional processes due to several apparent advantages in terms of material efficiency, resource efficiency, and product complexity and flexibility [1]. FDM reduces material wastage as it is not associated with material removal processes such as cutting or machining. FDM uses fewer resources in terms of tools and equipment as it solely relies on the extruding nozzle and the work bed to develop a complete product. In terms of product complexity and flexibility, the nozzle of an FDM printer is free to move in three different axes of X, Y and Z with minimal constraints while extruding the melted filament enabling a more complex product to be fabricated with high precision and intricacy [2]

Despite the conveniences, FDM is also associated with several limitations regarding the feasible size of parts [1], surface imperfection [3], poor mechanical strength [4] and the undeniable high cost of FDM equipment and accessories [5]. FDM printed parts are considered anisotropic due to the build direction of the extrusion. The mechanical characteristics, such as tensile strength, are thus substantially affected by stacking layers in various orientations.

The manufacture of an FDM printed product relies on several significant factors that directly influence the final quality of the product. Aside from the types of filaments used, the most crucially looked at factors are the FDM process parameters. Default parameters from handbooks are typically supplied by manufacturers to provide a range of parameter options to print with. However, an inadequate combination of printing

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parameters can impact the surface roughness and mechanical strength of a product while simultaneously wasting valuable resources [3], [6]–[9].

It has been acknowledged that FDM products with a higher density of materials perform better in mechanical strength such as tensile strength [6], [8], [10]–[13]. However, printing products with more material are not cost and time efficient. In an effort to produce economically feasible and mechanically robust products, additional research is necessary to recognize common printing parameters affecting these aspects to benefit future optimization.

FDM PROCESS PARAMETERS

The FDM process consists of multiple process parameters or printing parameters that set the overall mechanical and aesthetical performance of a manufactured product while also affecting the efficiency of the printing process. These process parameters are layer height, infill density, infill pattern, printing temperature, printing speed, outer shell speed, raster angle, raster width, number of contours and air gap [13]–[16]. The description of each of the parameters is specified below.

- Layer height: The cross-sectional height of a single layer of melted thermoplastic along the Z axis.
- Infill density: The amount of material deposited within the walls of printed products.
- Infill pattern: The supporting pattern deposited within the walls of printed products.
- Printing temperature: The melting temperature of the nozzle head of the hot end.
- Printing speed: The rate at which the build nozzle traverses the XY plane while depositing material on the build platform.
- Outer shell speed: The rate at which the part outermost perimeter (shell) is printed
- Raster angle: The angle between two rasters during direction change.
- Raster width: The width of the deposition route taken to create the specified part
- The number of contours: The number of times the print head circles the layer to outline the frame.
- Air gap: The distance between two adjoining rasters.

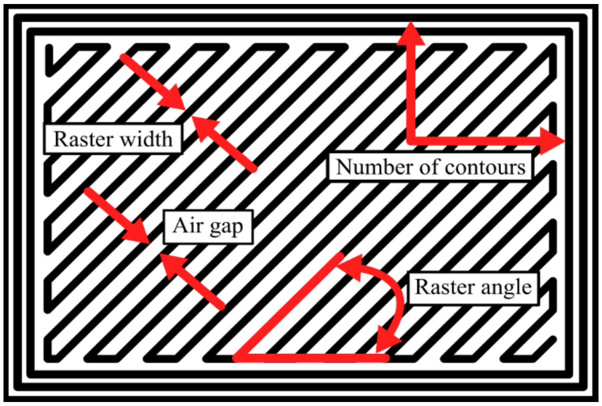

Figure 1 Tool path parameter

EFFECT OF PRINTING PARAMETERS ON PRINTED PARTS

There are numerous complications regarding the impact each of the parameters poses on the printed product. Though, the most highly regarded problem of physically functional FDM printed parts is concerning mechanical performance. One such performance is tensile strength, often linked to material consumption as products printed with more material are stronger in terms of load-bearing capacity. However, products printed with more material will consume more resources in terms of material, time and energy; ergo, raising the production cost.

A study of flexural and tensile strength was conducted by Jatti et al [12], supported this claim. The study was conducted by printing specimens with varying constant values and variable values. According to Figure 2 and Figure 3, it was reported that a selected infill percentage of 100%, printing speed of 50 mm/s, layer height of 0.16 mm and printing temperature of 200°C individually yield the highest tensile strength. Jatti et al. [12], claimed that increasing the infill percentage increases the amount of material being deposited into the printing specimen, hence increasing the tensile strength as well. Meanwhile, it was noted that with an increase in print speed and layer height, tensile strength decreases. Contrary to that, the study also mentioned that tensile strength maximizes with higher temperature due to better layer adhesion.

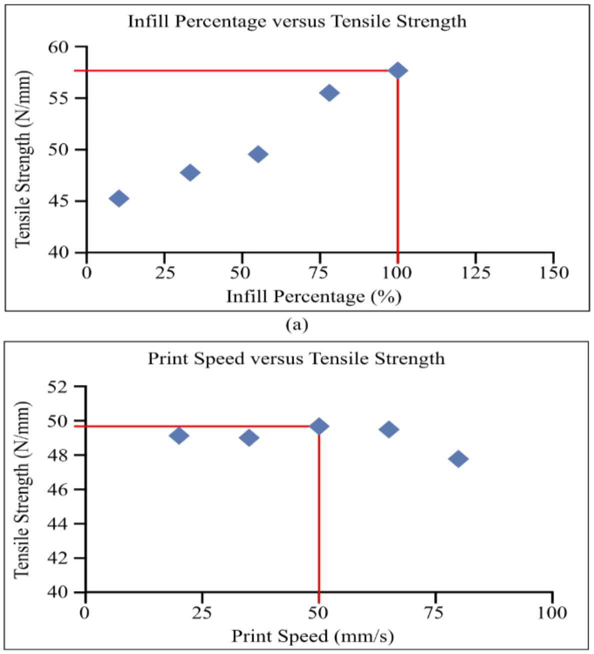

Figure 2 (a) Infill percentage versus tensile strength (b) Print speed versus tensile strength [12]

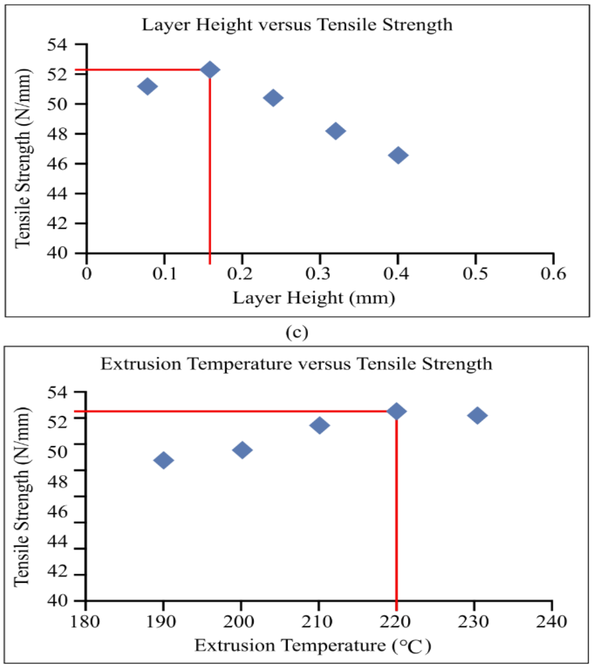

Figure 3 (c) Layer height versus tensile strength (d) Extrusion temperature versus tensile strength [12]

Yadav et al. [10], substantiate the finding while conducting a study on Polyethylene terephthalate glycol or PETG to optimise infill density, infill pattern and printing temperature by measuring the tensile strength of products. It was concluded that printing temperature and infill density similarly impacted tensile strength. However, exceeding a certain value of printing temperature seems to negatively impact the tensile strength of the printed product. The maximum tensile strength of 44 N/mm^2 was recorded for parts printed at 225°C with an infill density of 40%. Then, experimentally proven data of an optimised solution confirmed that parts printed at 240°C with 45% infill density recorded higher tensile strength of 46 N/mm^2. As a result, overall tensile strength increased by 4% after the increment of printing temperature and infill percentage.

Similar findings regarding infill percentage were recorded by Goudswaard et al. [6], who conducted tensile tests over several specimens with a unique combination of process parameters. It was documented that the experimental results agreed with the literature stating that adding to the infill percentage, top/bottom layers and the solid shell will simultaneously increase the ultimate tensile strength (UTS) while increasing the layer height will result in decreasing UTS. Meanwhile, the categoric variable of build orientation shows that specimen printing in the Y-direction yields the highest UTS (38 MPa) followed by the X-direction (35 MPa) and then the Z-direction (25 MPa). Figure 4 illustrates the positive correlation of UTS to infill percentage, top/bottom layers, and solid shells and the negative correlation of UTS to layer height while UTS is shown to be the highest for Y-direction and lowest for the Z-direction. Figure 4 shows that the infill percentage had the greatest influence on the UTS.

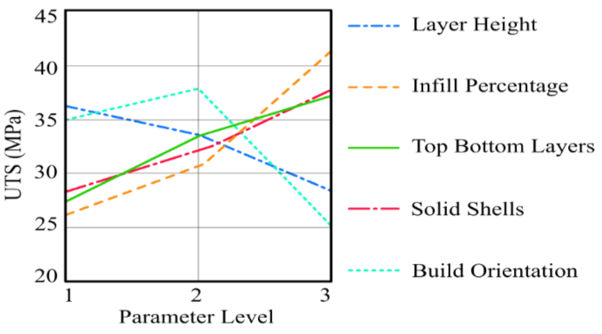

Figure 4 Normalised impact of variables on the ultimate tensile strength (UTS) [6]

Deshwal et al. [8], observed similar results after testing for tensile strength of multiple PLA plus specimens with various infill densities, printing speed, and temperatures. The finding indicated that raising the infill percentage to 100% and temperature to 210°C simultaneously maximized tensile strength (45.27 MPa) due to better layer fusion and rising internal forces between the extruded layers. The printed specimen also has a specific optimal printing speed of 100 mm/s. Any value lower or higher than 100 mm/s will result in a specimen with low tensile strength. Poor selection of printing speed will lead to inconsistent raster and limit proper bonding between the rasters.

Singh et al. [9], conducted a study to obtain optimal FDM printing parameters to maximize three mechanical strengths and noticed several similar interactions between the parameters and the responses. The summary of parameters to the recorded minimum and maximum readings of tensile strength, compressive strength, and flexural strength is shown in Table 1. The optimal printing temperature for the maximum reading of all three strengths is 230 ℃. An increase in printing temperature to 240℃ has been shown to reduce both tensile strength and flexural strength to a minimum while an increase in printing temperature to 250℃ has been shown to reduce compressive strength to a minimum. Increasing layer height by 0.1 mm has been shown to increase tensile strength and flexural strength to maximum. Meanwhile, minimum, and maximum compressive strength is recorded at the sample printed using 0.2 mm layer height. A triangular infill pattern was shown to be superior to a zigzag infill pattern in terms of maximizing all the strengths.

Table 1 Parameters of recorded minimum and maximum readings of tensile strength, compressive strength, and flexural strength [9].

Mechanical Strength	Parameter	Min Reading (N)	Max Reading (N)
Tensile Strength	Temperature (℃)	240	230
	Layer Height (mm)	0.1	0.2
	Infill Pattern	Zigzag	Triangular

Table 2 Parameters of recorded minimum and maximum readings of tensile strength, compressive strength, and flexural strength [9], Continued.

Compressive Strength	Temperature (℃)	250	230
	Layer Height (mm)	0.2	0.2
	Infill Pattern	Zigzag	Triangular
Flexural Strength	Temperature (℃)	240	230
	Layer Height (mm)	0.1	0.2
	Infill Pattern	Zigzag	Triangular

SUMMARY OF COMMONLY STUDIED PRINTING PARAMETERS

It is worth mentioning that most of the literature is based on several similar selected printing parameters. The distinctively recurring printing parameters of the works of literature are infill percentage, layer height, printing temperature and printing speed. Johansson [17], states that the key elements that influenced the quality of the printed result, were printing temperature, printing speed, and layer height. The findings indicated that increasing the printing temperature from 190 ℃ to 250 ℃ increased load capacity seven-fold. Furthermore, compared to a quicker printing speed of 130 mm/s, a slower printing speed of 10 mm/s shows a better bonding connection between extruded layers. Aside from that, printing using 0.1 mm layer height instead of 0.4 mm increased part's load capacity by 91%.

Layer height, infill percentage, printing speed, and printing temperature are generally concerned parameters when it comes to FDM, according to more recent research by Nguyen et al. [11], who established a set of optimal printing parameters simultaneously satisfying tensile strength, material and time consumption. Nguyen et al. [11], stated that infill percentage and printing temperature were the two most influential printing parameters affecting the weight of the printed part while layer height and printing speed were more influential towards printing time. It was noticed that parts printed with higher weight and longer printing time have higher tensile strength. A summary of the range of the four common printing parameters and the corresponding results on tensile strength and material consumption are shown in Table 3. It can be seen that to produce economically feasible and robust products, compromises must be made because ideal parameters computed for the weight reduction of a part do not ensure high tensile strength [11], [18]. Further study is needed to determine possible best combinations of these printing parameters that utilize less material while maintaining high tensile strength.

Table 3 A summary of the range of the four common printing parameters and the corresponding results on tensile strength and material consumption.

Source	Material	Layer height (mm)	Infill percentage (%)	Printing temperature (℃)	Printing speed (mm/s)	Material Consumption	Tensile Strength
(Yadav et al., 2020) [10]	ABS, PETG, multi-material	0.2 (fixed)	20 - 60	210 - 240	70 - 80	NA	1. Increase with higher printing temperature and infill density.
(Goudswaard et al., 2021) [6]	NA	0.1, 0.2, 0.3	20, 60, 100	200 (fixed)	60 (fixed)	NA	1. Increased with a higher infill percentage. 2. Increased with a lower layer height.
(Dev & Srivastava, 2020) [7]	ABS	0.2, 0.3, 0.4	20, 50, 80	NA	NA	1. Increase with higher infill density.	NA
(Deshwal et al., 2020) [8]	PLA+	NA	20, 60, 100	190, 200, 210	50, 100, 150	NA	1. Increased with higher infill percentage and temperature. 2. Decreasing with speed above or below 100 mm/s.
(Singh et al., 2022) [9]	Copper reinforced ABS	0.1, 0.15, 0.2	NA	230, 240, 250	NA	NA	1. Increased with a lower layer height and higher in printing temperature.
(Vishwas & Basavaraj, 2017)[19]	ABS	0.1, 0.2, 0.3	50 (fixed)	240 (fixed)	NA	NA	1. At maximum printed using 0.2 mm layer height
(Nidagundi et al., 2015) [20]	ABS	0.1, 0.2, 0.3	NA	NA	NA	NA	1. Increase with the lowest layer height.
(Nguyen et al., 2020) [11]	PLA	0.06, 0.1, 0.2, 0.3	20, 40, 60, 80	190, 200, 210, 210	30, 40, 50, 60	1. Increase with high infill percentage.	1. Increase with an increase in material consumption.

Table 2 A summary of the range of the four common printing parameters and the corresponding results on tensile strength and material consumption, Continued.

(Yang et al., 2018) [21]	PLA	0.1, 0.2, 0.3	NA	200, 215, 230	NA	NA	1. Increases with higher layer height. 2. Increase with higher printing temperature. 3. Decrease with a lower speed.
(Mohamed et al., 2016) [18]	Polycarbonate /ABS blend	0.1270, 0.1778, 0.2540, 0.3302	NA	NA	NA	1. Decrease with higher layer height.	NA
(Tang et al., 2020) [22]	PLA	0.1 (fixed)	100	200, 210, 220, 230, 240	30, 40, 50, 60	NA	1. Increase with higher printing speed. 2. Increase higher printing temperature.
(Jatti et al., 2019) [12]	PLA	0.08, 0.16, 0.24, 0.32, 0.4	10, 33, 55, 78, 100	190, 200, 210, 220, 230	20, 35, 50, 65, 80	1. Increase with a higher infill percentage.	1. Increase with a higher infill percentage. 2. Decreases higher layer height. 3. Increase with higher temperature.
(Hsueh et al., 2021) [23]	PLA, PETG	0.2 (fixed)	20 (fixed)	180 - 220 (PLA), 225 - 245 (PETG)	35 - 45 (PLA), 25 - 35 (PETG)	NA	1. Increase with higher temperature. 2. The tensile strength of PLA increases with higher speed. 3. Tensile strength PETG decreases with higher speed.
(Ansari & Kamil, 2021) [24]	PLA	0.2 (fixed)	100 (fixed)	190, 210, 230	40, 50	NA	1. Increase with higher printing speed and higher printing temperature.
(Sood & Pradhan, 2020) [25]	PLA	0.2, 0.3, 0.4	NA	205, 210, 215	NA	NA	1. Optimum at printing temperature 210℃. 2. Increase with a lower layer height.
(Asadollahi-Yazdi et al., 2018) [26]	ABS	0.1, 0.13, 0.2, 0.25, 0.33, 0.35	100 (fixed)	230 (fixed)	90 (fixed)	1. Increase with higher layer height.	2. Optimum at 0.1-layer height.

Table 2 A summary of the range of the four common printing parameters and the corresponding results on tensile strength and material consumption, Continued.

(Teharia et al., 2022) [27]	PLA	0.1, 0.15, 0.2	NA	190 - 210	40, 50, 60, 70	NA	1. Decrease with higher speed. 2. Increase with higher layer height. 3. Increase with higher temperature.
(Johansson, 2016) [17]	TPU, PLA	0.1, 0.2, 0.3, 0.4	30 (fixed)	230 (fixed)	40 (fixed)	NA	1. Increased 7 times when printed at 270 ℃ compared to 190 ℃. 2. Increased 91% when printed with a layer height of 0.1 compared to 0.2. 3. Increased with a minimal print speed of 10 mm/s compared to 130 mm/s.
(D’Addona et al., 2021) [28]	PLA	0.15, 0.2, 0.25, 0.3	55, 65, 75, 85	NA	70, 80, 90, 100	1. Decrease with higher layer height. 2. Decrease in infill density and printing speed.	NA
(Vishwas et al., 2018) [29]	ABS, nylon	0.1, 0.2, 0.3	50	240	NA	NA	1. Increase with a lower layer height.
(Mohamed et al., 2021) [30]	PC-ABS	0.1270, 0.2540, 0.3302	NA	NA	NA	NA	NA
(Sai et al., 2020) [31]	PLA	0.1, 0.15, 0.2, 0.25, 0.3	30, 40, 50, 60, 70	NA	NA	1. Decrease with higher layer height and lower infill density.	NA
(Nagendra et al., 2021) [16]	Nylon with 2% aramid	0.2, 0.3, 0.4	70, 80, 90	280, 290, 300	NA	NA	NA
. (Mohanty et al., 2022) [32].	ABS M30	0.127, 0.178, 0.254	NA	NA	NA	NA	NA

Table 2 A summary of the range of the four common printing parameters and the corresponding results on tensile strength and material consumption, Continued.

(Fountas & Vaxevanidis, 2021) [33]	ABS	0.09, 0.19, 0.29	10, 20, 30	NA	NA	NA	NA
(Saad et al., 2019) [3]	PLA	0.18 - 0.3	NA	185 - 205	36 - 60	NA	NA
(Deswal et al., 2019) [14]	ABS	0.12 - 0.4	0 - 100	NA	NA	Decrease with a low infill percentage.	NA
(Camposeco-Negrete, 2020) [13]	ASA	0.18, 0.25, 0.33	NA	NA	NA	Decrease with a lower layer height.	1. Increase with a higher infill percentage.

DISCUSSION

This section discusses the key findings, gaps in the literature, and future directions for study in the optimization of FDM printing parameters based on presented research on common printing parameters. The path of future studies may help to improve the FDM process' drawbacks to achieve optimal tensile strength with the least amount of material consumption in industrial mass production.

COMMON PRINTING PARAMETERS MAINLY IMPACTING TENSILE STRENGTH AND MATERIAL CONSUMPTION

Layer height: One of the most common printing parameters involved in most studies is layer height. According to the summary in Table 3 the common range of layer height selected by previous researchers is between 0.06 mm to 0.4 mm. The layer height does not exceed a height of 0.4 mm because current FDM machines generally utilize a standard nozzle diameter of 0.4 mm[34]. The selection of layer height is usually determined by the size of the nozzle used. According to a study by Irene Buj-Corral [35], the recommended layer height or layer height optimal for printing thermoplastic is between 0.5 and 0.8 multiplied by the nozzle diameter. Considering the standard 0.4 mm diameter, the layer height should be between 0.2 mm to 0.23 mm. It is worth acknowledging from Table 3 that the type of material or filament used does not seem to influence the selection of layer height.

Infill percentage: The amount of infill density of a printed part is usually selected based on how the parts will be utilized. Products that are printed solely as a model for visual purposes are usually printed with a lower infill percentage to minimize material usage. Meanwhile, end-use products are printed to be mechanically stronger with a higher infill percentage. Despite the advantage of being mechanically stronger, products printed with higher infill density will logically cost more as it demands more in terms of material and time. According to Table 3, the range of infill density selected for studies ranges from 20% to 100%.

Printing temperature: Optimal printing temperatures for filaments are usually provided by the manufacturer in certain ranges depending on the type of material. Printing temperatures are different for each type of material due to the different melting points of each material used. However, these temperatures are not specifically catered to the type of FDM machine used. Different printers have different set of cooling features that affect the adhesion of layers differently. Therefore, it is essential to identify the optimal printing temperature specifically for the type of material and printer used. Unfortunately, some studies did not specifically mention the type of printer used. Therefore, the printing temperature from recent studies in Table 3 shown in Table 4 is only summarized according to the material being used. Aside from materials listed in Table 4, composite materials were also used in some studies. However, further studies are required to properly assign suitable printing temperatures for these materials as most of the materials are still under development and not readily obtainable in the market.

Table 4 Ranges of printing temperature for each material

Material	Temperature (℃)
PLA	180 - 240
PLA+	190 - 210
ABS	210 - 240
PETG	210 – 245
Nylon	240

Printing speed: Aside from printing temperature, printing speed is also a parameter commonly suggested by manufacturers as it also depends on the type of material used. It is worth noting that printing speed also varies according to the FDM machine being used. However, insufficient information regarding the printer being used limits the findings on optimal printing speed for a specific printer. The range of printing speeds used in previous studies listed in Table 3 are shown in Table 5

Table 5 Ranges of printing speed for each material

Material	Printing speed
PLA	20 - 100
PLA+	50 - 150
ABS	70 - 90
PETG	25 - 80

EFFECTS OF COMMON PRINTING PARAMETERS ON MATERIAL CONSUMPTION

This review is focused on identifying common printing parameters that impact both responses of maximum tensile strength and minimal material consumption. However, is also important to understand the impacts of these printing parameters on these responses separately. In summarizing Table 3, it was reported that a higher infill percentage increases material consumption as more materials are deposited within the product [7], [11], [12], [14], [28], [31]. Aside from that, several studies also stated that material consumption increases with a lower layer height [18], [28], [31]. However, Asadollahi-Yazdi et al. [26] and Negrete [13] disagreed with these findings and identified that material consumption increases with a higher layer height [13], [26]. Meanwhile, D'Addona et al. [28] required that material consumption increases with higher printing speed [28].

EFFECTS OF COMMON PRINTING PARAMETERS ON TENSILE STRENGTH

Focusing on tensile strength, the majority of studies that were conducted on printing temperature agrees that tensile strength increases with higher printing temperature [8]–[10], [12], [17], [21], [23]–[25], [27]. Higher printing temperature melts the filaments to a higher degree making them more fluid for a more cohesive adhesion between the layers. Contradicting this, Tang et al. tested multiple PLA specimens printed at a temperature between 200℃ – 240℃ and a constant layer height of 0.1 mm then concluded that tensile strength decreases when the printing temperature exceeds 230 ℃. Meanwhile, all studies concerning infill density wholly agree that higher infill density yields products with higher tensile strength [6], [8], [10], [12], [13]. Most studies in Table 3 concluded that tensile strength increases with a lower layer height [6], [9], [12], [17], [19], [20], [25]. Shilpesh R. and Harshit K. mentioned that lower layer height benefits tensile strength as deposited filaments are flatter with higher surface contact for better adhesion[36]. However, a small percentage disagreed with this finding and conflicted that tensile strength increases with a higher layer height [21], [27]. There were multiple conflicting findings based on printing speed regarding high tensile strength. Yang et al., Tang et al. and Ansari and Kamil noted that printing PLA at higher speed results in higher tensile strength ([21], [22], [24] while Johansson and Teharia et al. argued that printing PLA with a lower printing speed produces specimen with a higher tensile strength [17], [27]. However, a study by Hsueh et al. proved that PLA printed at a higher speed has stronger tensile strength while PETG printed at a lower printing speed has stronger tensile strength [23]. Though a study by Deshwal et al. focusing on PLA+ suggested that a printing speed of 100 mm/s is optimal for maximum tensile strength [8]. It could be argued that these studies utilized different types of 3D printers with the possibility of the uncertainty of distinct ambient temperatures producing conflicting results.

TENSILE STRENGTH AND MATERIAL CONSUMPTION CORRELATION

It was previously established that material consumption relates closely to tensile strength as parts printed with more materials tend to outperform parts printed with less material in terms of mechanical strength [11], [12] However, in the spirit of printing mechanically robust and commercially viable products, both responses of tensile strength and material consumption are to be considered equally important. Through analyzing the findings of previous research, it is observed that some of these parameters are interdependent. Most of these existing studies identified an optimum combination of parameters by applying numerical optimization. However, most of the optimization conducted was based on a single response optimization. Ideally, optimal printing parameters should be obtained through multi-objective optimization to fulfil both higher tensile strength and low material consumption.

CONCLUSION

This paper highlights commonly influential process factors such as layer height, infill density, printing temperature, and printing speed, as well as how each of these characteristics influences a product's tensile strength and material consumption. It can be observed that these printing parameters are all interdependent and should be simultaneously optimized by equally considering both tensile strength and material consumption through utilizing a multi-objective optimisation approach. There is still limited research using multi-objective optimisation especially for identifying optimal FDM printing parameters. Functional parts in a real-world application typically require the satisfaction of multiple requirements such as tensile strength, material consumption, dimensional accuracy, surface roughness and many more. Therefore, additional studies on multi-objective optimisation to economically commercialize the technology for various industrial applications are required.

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