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Review on Effect of Process Parameters used in Fused Deposition Modelling (FDM) 3-D Printing

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ABSTRACT:
Fused Deposition Modelling (FDM) is a widely used additive manufacturing technology that enables cost-effective and customizable part production. However, the quality, mechanical properties, and accuracy of FDM-printed parts are significantly influenced by various printing parameters. This review systematically examines the effects of key process parameters, including layer height, nozzle temperature, printing speed, infill density, build orientation, dimensional accuracy, and mechanical performance of printed components. The role of material selection in combination with process optimization is also explored. Recent advancements in parameter optimization techniques, including artificial intelligence and machine learning-based approaches, are discussed. This review provides a comprehensive understanding of how printing parameters impact FDM-printed part quality and offers insights into future research directions for improving process efficiency and product performance

Keywords: Fused Deposition Modelling, Printing Parameters, Mechanical Properties, Process Optimization, 3D Printing, Additive Manufacturing

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I. INTRODUCTION

Fused Deposition Modelling (FDM) is one of the most widely used additive manufacturing (AM) technologies, known for its simplicity, cost-effectiveness, and versatility. Developed in the late 1980s and commercialized by Stratasys in the early 1990s, FDM has revolutionized rapid prototyping and low-volume production across various industries, including aerospace, automotive, healthcare, and consumer goods. Unlike traditional subtractive manufacturing methods, which remove material from a solid block, FDM builds objects layer by layer through the controlled extrusion of thermoplastic filaments. This process enables the creation of complex geometries that would be challenging or impossible to achieve using conventional manufacturing techniques.

The FDM process begins with a digital 3D model, which is sliced into multiple layers using specialized slicing software. The sliced data is then sent to the 3D printer, where a heated nozzle extrudes molten thermoplastic material onto a build platform. The material solidifies upon deposition, and successive layers are added until the final part is completed. Commonly used materials in FDM include polylacticacid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate glycol (PETG), and high-performance polymers such as polyether ether ketone (PEEK) and Ultem. The choice of material depends on the specific application requirements, such as mechanical strength, thermal resistance, and biocompatibility.

One of the key advantages of FDM is its ability to produce customized parts with minimal material wastage. It allows for rapid prototyping and on-demand manufacturing, reducing lead times and costs associated with traditional manufacturing processes. However, the quality of FDM-printed parts is highly dependent on various printing parameters, including layer height, nozzle temperature, print speed, infill density, build orientation, and cooling conditions. These parameters significantly affect the mechanical properties, surface finish, dimensional accuracy, and overall performance of the printed parts.

Layer height, for instance, determines the resolution of the printed object, with smaller layer heights yielding finer details but increasing print time. Nozzle temperature affects material flow and layer adhesion, where improper settings can lead to weak interlayer bonding or excessive warping. Print speed influences the rate of material deposition, impacting print quality and structural integrity. Infill density and pattern dictate the internal structure of the part, affecting weight, strength, and material consumption. Build orientation plays a crucial role in determining anisotropic behaviour, as FDM parts exhibit different mechanical properties along different axes due to their layer-by-layer construction. Proper cooling settings are also essential to prevent defects such as stringing and warping, especially in high-temperature materials. Despite its advantages, FDM has inherent limitations, including anisotropic mechanical properties, surface roughness, and the need for post-processing to enhance appearance and strength. Researchers and engineers are continuously exploring optimization techniques to improve FDM-printed part performance through parameter tuning, material modifications, and advanced post-processing methods. Recent advancements in artificial intelligence and machine learning have also contributed to predictive modelling for optimal parameter selection, further enhancing print quality and efficiency.

This review aims to provide a comprehensive analysis of the effect of various printing parameters on FDM-printed parts. By examining recent studies and experimental findings, this paper highlights the relationships between process parameters and key performance attributes, offering insights into best practices and future research directions in FDM technology. Understanding these factors is crucial for optimizing print settings, reducing defects, and expanding the capabilities of FDM in industrial and commercial applications.

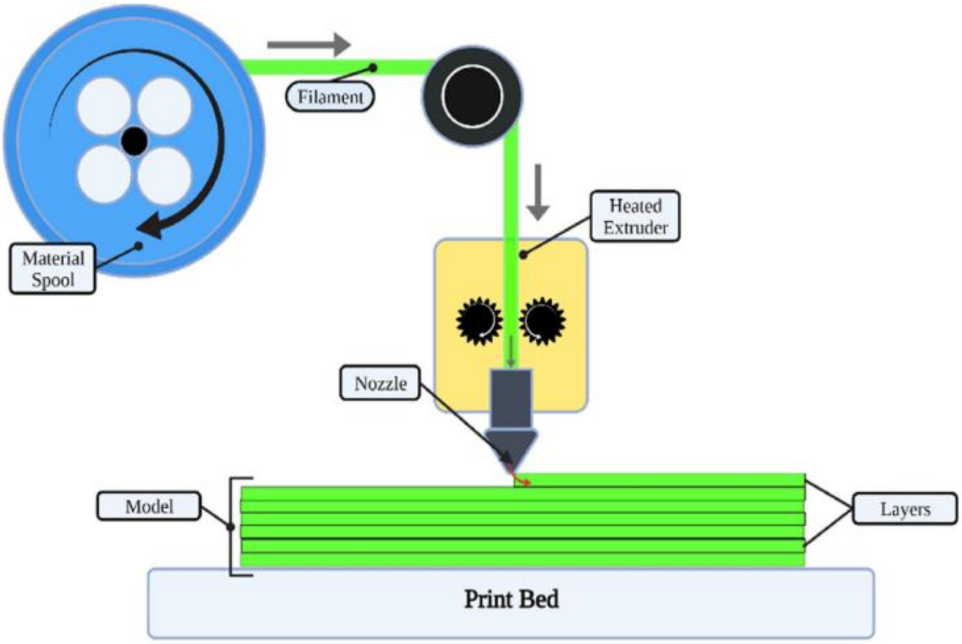

Fig.1 FDM 3D Printing [2]

II. LITERATURE REVIEW

2.1 Jayant Giri et. al. [1] performed experiment on a dog bone structure (Fig.2) printed by FDM using PLA filament. They used constant parameters such as infill density 60%, printing speed 60mm/s, extruder temperature 200 degree Celsius, etc. They performed experiment on Universal Testing Machine (UTM) to test tensile strength of various samples. Those samples had variable build orientation (horizontal and vertical), layer thickness ranging from 0.2 to 0.4 mm, and cooling rate ranging from 25 to 100%. They found that for horizontal orientation, the cooling rate had negligible effect on tensile strength and when layer thickness was increased the tensile strength decreased. And for vertical orientation, higher cooling rate decreased tensile strength and effect of layer thickness was same as horizontal orientation.

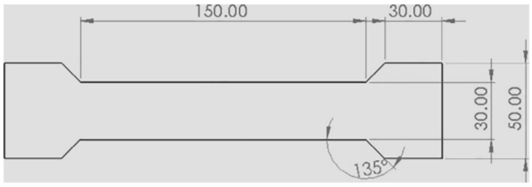

Fig.2 Dog bone structure used in paper [1]

2.2 Krishna Mohan et al [2] performed experiment on a different type of structure (Fig.3) and using ABS material filament in FDM printing. They used parameters as follows, wall thickness 0.8, 1.2, 1.6mm, infill density 20, 35, 50%, build plate temperature 80, 95, 110 Celsius, printing speed 30, 47.5, 65 mm/s, layer thickness 0.1, 0.2, 0.3mm and extrusion temperature 225, 232.5, 240 Celsius. In their paper, they found effect of all these parameters on the dimensional accuracy of printed object. And the result was, increasing the printing speed increased accuracy due to higher shear rates, increasing the layer thickness decreased the accuracy and lastly when infill density was increased, the dimensional accuracy decreased.

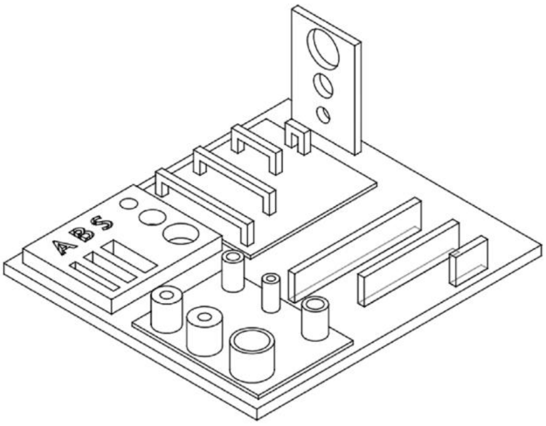

Fig.3 Isometric vies of designed samples [2]

2.3 Aboma Wagari and Hirpa Lemu [3] also performed experiment on UTM machine (Fig.4) but this time using ULTEM 9085 material in FDM printing. The used parameters are as follows, air gap -0.254 and 0.00m, raster width 0.4064 and 0.7814mm, raster angle 0 and 90 degree, contour number 1 and 5, contour width 0.4064 and 0.7814mm. They found that low air gap, low raster width, high contour number and higher value of contour width improved tensile strength, and the o degree raster angle showed higher tensile strength than 90 degree samples. The influence of the raster angle was the highest

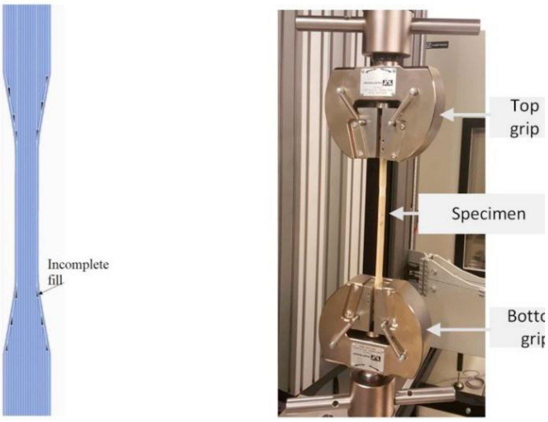

Fig.4 Design of Sample and UTM machine [3]

2.4 Peng Wang et al [4] in their paper they tested 3 variants of PEEK material (Fig.5) i.e PEEK, CF/PEEK, GF/PEEK. And they tested their tensile, flexural and impact strength using different parameters like nozzle temperature (400 to 440 Celsius), platform temperature (240 to 280 Celsius), printing speed (5 to 25 mm/s), layer thickness (0.1 to 0.3mm). the results were as follows, increasing the nozzle temperature, increased tensile strength (CF/PEEK exhibited more tensile strength than GF/PEEK), flexural strength also increased (GF/PEEK showed more improvement compared to CF/PEEK), impact strength decreased. Increasing the printing speed decreased all three strengths, for PEEK tensile strength decreased by 10%, flexural strength decreased by 11%, for CF/PEEK tensile by 8%, flexural by 8% and impact by 55% and for GF/PEEK tensile by 10%, flexural by 9%, impact by 68%. Next when layer thickness increased, all strength decreased. And lastly when platform temperature increased, tensile strength for CF/PEEK increased by 15% and flexural strength increased by 10 %.

Fig.5 Variants of PEEK material dog bone structure [4]

2.5 Liviu Marsavina et al [5] performed experiment on PLA material in FDM printing and tested its tensile strength. They used parameters as follows, growing direction horizontal and vertical (Fig.6), orientation 0, 45 and 90degree, and filament colour purple, white, black, gray, red and orange. The result found were as follows, the tensile strength for horizontal growing direction was higher than vertical (+2.1% than 0 degree in 45 degree and +8.8% in 90 degree orientation), next the 0 degree orientation softening behaviour after maximum load, quasi-brittle fracture was found in 45 degree orientation. And the tensile strength for different colours was, purple – 50.88 MPa, white – 39.01 MPa, black – 48.24 MPa, gray – 43.08 MPa, red – 50.11 MPa, orange – 45.04 MPa.

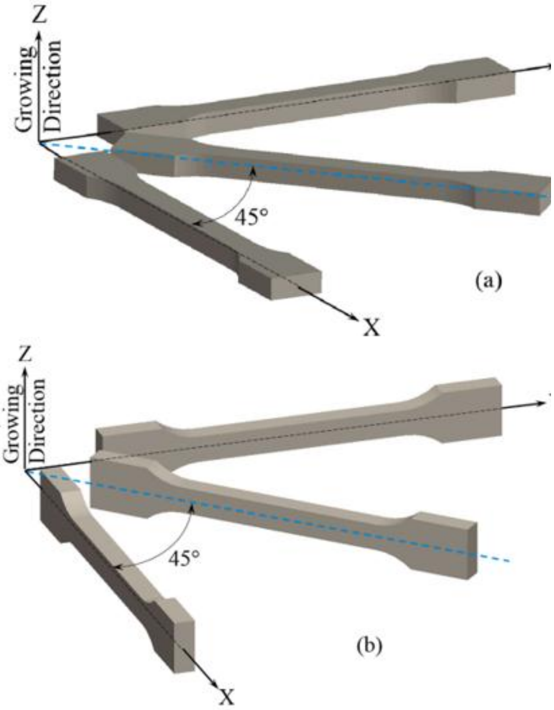

Fig.6 Printing direction and orientation:
(a) Horizontal and (b) Vertical growing [5]

2.6 Anis Ansari and M. Kamil [6] used PLA material in FDM printing and found dimensional deviation in different samples. These different samples were having parameters like, printing speed (40 and 50 mm/s), and extrusion temperature (190, 210, 230 Celsius). The results were found as follows, increasing the printing speed increased deviation but also increased tensile strength. Increasing Extrusion temperature decreased deviation and increased tensile strength.

2.7 Saty Dev and Rajeev Srivastava [7] performed experiment in their paper on ABS material in FDM printing and tested flexural strength of various samples. These samples had multiple combination (Fig.7) of different parameters like, layer thickness (0.1, 0.2, 0.3 mm), nozzle temperature (220,230,240 Celsius), print head speed (30, 50, 70 mm/s). The results were as follows, moderate thickness showed better flexural strength compared to higher and lower values of layer thickness. Higher nozzle temperature enhanced bonding hence improved strength. And lastly print head speed improved strength when increased.

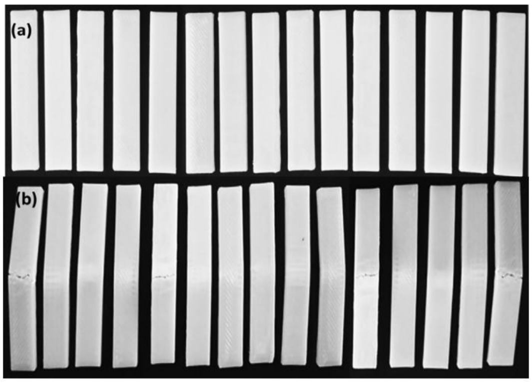

Fig.7 Samples of different combination before and after testing [7]

2.8 M. Azadi et al [8] tested strength of printed sample (Fig.8) of ABS and PLA material in FDM printing. Multiple combination of different parameters were used like printing direction (horizontal and vertical), and different stress levels were applied (5, 10, 15 MPa). The results were as follows, horizontally printed samples exhibited longer fatigue lifetime under low stress levels while under high stresses, both orientation showed similar fatigue behaviour. PLA had greater tensile and fracture strength than ABS but failed at lower strains. ABS exhibited better flexibility under cyclic loading. Under 5, 10, 15 MPa, horizontal PLA samples performed 813%, 557%, 1104% better than vertical specimens respectively.

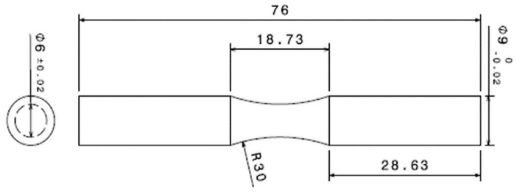

Fig.8 Diagram of sample printed [8]

2.9 Chamil Abeykoon et al [9] performed 3 tests which are tensile, bending and compressive tests (Fig.9) and using different parameters like infill density (25, 30, 40, 50, 70, 90, 100%), printing speed (70, 80, 90, 100, 110 mm/s), infill pattern (linear, hexagonal, moroccocanstar, catfill, sharkfill, diamond, hilbert), printing temperature (200, 205, 215, 230degree Celsius), infill material (PLA, ABS, CRF-PLA, CRF-ABS, CNT-ABS). And the results were as follows, increasing infill density increased tensile modulus (Young’s modulus) for pure PLA, increasing infill or printing speed upto 90 mm/s, increased Tensile modulus but further increasing it, decreased tensile modulus in pure PLA. Tensile modulus for hexagonal pattern was lowest and for linear patter was highest in pure PLA. For infill material pure ABS had lowest and CFR-PLA had the highest Tensile modulus, Bending modulus and Compressive modulus. Refer Fig.10a, Fig.10b, Fig.10c, Fig.10d, Fig.10e, Fig.10f, Fig.10g

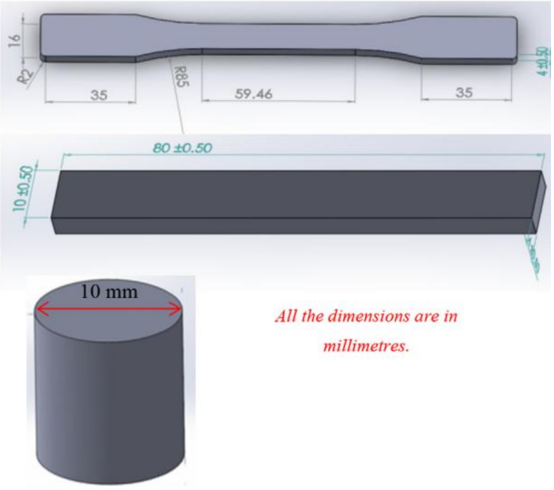

Fig.9 Samples for Tensile test, Bending test and Compressive test respectively [9]

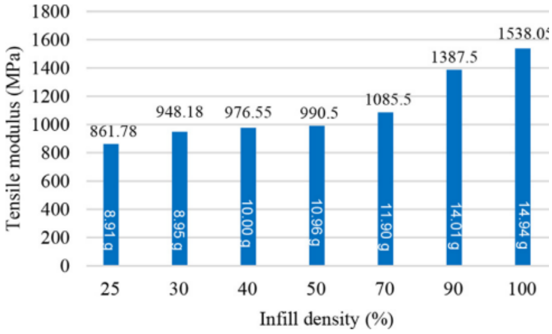

Fig.10a Results of Infill density variation in pure PLA [10]

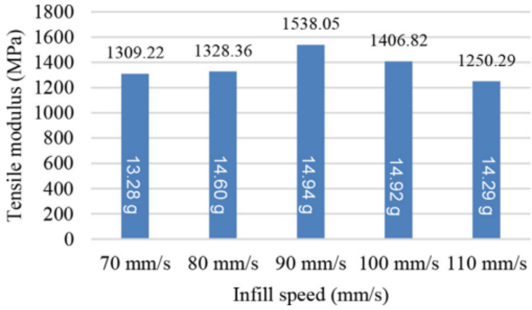

Fig.10b Results of Infill speed variation in pure PLA [10]

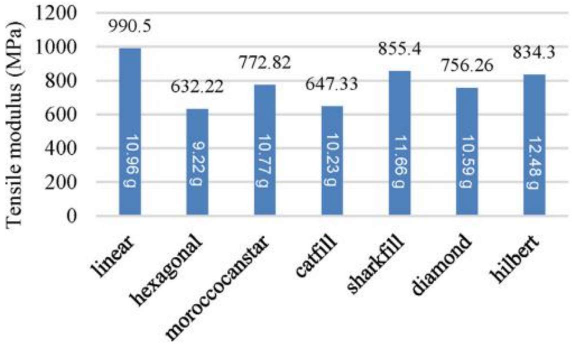

Fig.10c Results of Infill pattern variation in pure PLA [10]

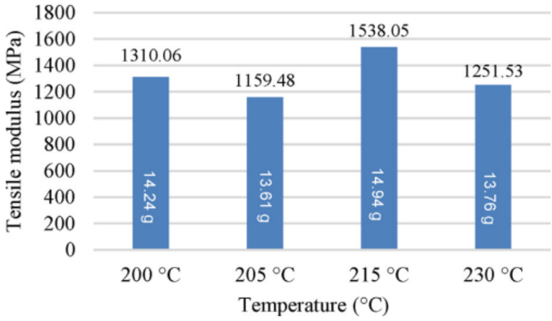

Fig.10d Results of Temperature variation in pure PLA [10]

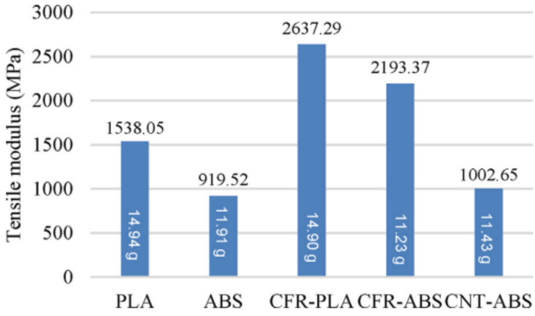

Fig.10e Results of Infill material variation on Tensile Modulus [10]

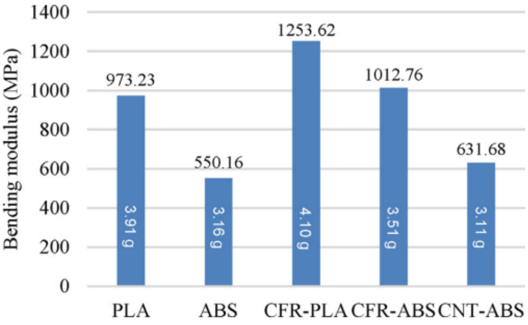

Fig.10f Results of Infill material variation on Bending Modulus [10]

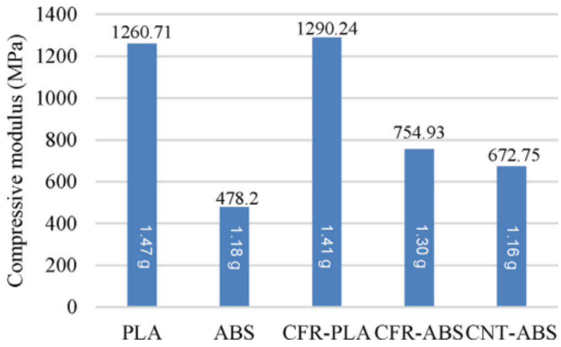

Fig.10g Results of Infill material variation on Compressive modulus [10]

III. RESULT TABLES

3.1 Table1: Results found in PLA material

Parameters	Effect	Observations
Layer thickness	When Increasing Layer thickness, the tensile strength decreases [1]	When the layer thickness increases, no. of layers decreases which reduces the bonding area density in a part [2], which leads to lower strength, but the build time decreases.
Printing Speed	Increasing the printing speed increases the tensile strength but decreases the accuracy [6]	Tensile strength increases when printing speed increases due to shear rate increases [2], but when the printing speed increases from 90mm/s, the strength starts decreasing [9]
Growing Direction	Horizontal growing direction have better tensile strength than vertical growing direction [5]	-
Printing Orientation	90 degree printing orientation have better tensile strength [5]	Best tensile strength is of 90 degree followed by 45 and 0 degree orientation [5]
Extrusion Temperature	Increasing the nozzle or extrusion temperature, increases the accuracy as well as tensile strength [5]	-
Infill Density	Increasing the infill density increases the tensile strength [9]	-
Cooling Rate	Increasing the cooling rate decreases the tensile strength [1]	Negligible effect on horizontal build but in vertical build increasing cooling rate decreases the tensile strength [1] because the material becomes more brittle
Printing Pattern	Linear pattern have best tensile strength [9]	Linear had the best tensile strength followed by sharkfill, Hilbert, moroccocanstar, diamond, catfill and worse for hexagonal respectively [9]

3.2 Table:2 Results found in ABS material

Parameters	Effect	Observations
Layer thickness	When Increasing Layer thickness, the accuracy decreases [2]	Moderate thickness had better flexural strength [7]

Printing Speed	Increasing the printing speed, increases the accuracy [2] as well as strength [7]	-
Extrusion Temperature	Increasing the nozzle or extrusion temperature, increases the flexural strength [7]	-
Infill Density	Increasing the infill density decreases the accuracy [2]	Higher infill density introduces more molten material in the part, which tends to flow outward

3.3 Table:3 Results found in ULTEM 9085 material

parameters	Effect	Observations
Air gap	Low air gap improves tensile strength by creating a denser structure.	Low-level air gap creates stronger parts by ensuring better filament overlap
Raster width	Low raster width improves tensile strength.	the influence of raster width is more noticeable with a 90º raster angle. However, the impact is not substantial.
Raster angle	Samples with 0º raster angle show higher tensile strength than 90º.	0º raster angle aligns filaments with the load direction, improving resistance to applied tensile load
Contour no	High contour number improves tensile strength, but the effect is minor.	High contour number adds longitudinal filaments aligned with the tensile load direction, improving the material's resistance to loading.
Contour width	Thicker contour width improves tensile strength.	Thicker contours provide stronger parts

IV. FDM PRINTING PARAMETERS

4.1 Layer thickness:

Layer thickness refers to the height of each individual layer of extruded material. It is a key parameter that affects print quality, strength, and print time. Increasing the layer thickness decreases tensile strength [1, 4]. But in case of ABS material printing, the moderate thickness had better flexural strength than lower and higher values of layer thickness [7]. Also when it comes to accuracy, higher layer thickness leads to less accurate dimensions of printed objects [2]. But an advantage of increasing the layer thickness is that it reduces the build time [1].

Tensile strength, flexural strength, and impact strength drop when thickness increased. Flexural strength of CF/PEEK and GF/PEEK drops by 14% at maximum when thickness reaches 0.3 mm [4].

Which means, if someone wants to print bulk models which does not require extreme accuracy, higher value of layer thickness is optimal. But in case accuracy is a must parameter, lower values of layer thickness are much more optimal.

4.2 Printing Speed:

Printing speed refers to how fast the print head moves while extruding filament. It is usually measured in millimeter per second (mm/s). It was seen that when the printing speed was increased, dimensional accuracy increased [2]. The explanation for this is that at higher print speeds, the shear rate (i.e. how quickly layers of fluid (in this case, molten filament) slide past each other during extrusion) exceeds, leading to decreased extrudate swell (i.e. the expansion of material after exiting the nozzle, this happens because the polymer molecules, compressed inside the nozzle, relax and expand once they exit). So as the extrudate swell decreases, the printed model becomes more accurate.

Increasing speed reduces tensile, flexural, and impact strength. Impact strength significantly drops, particularly for fiber-reinforced composites [4].

For PEEK, tensile strength decreases by 10% and Flexural strength decreases by 11% [4]

For CF/PEEK, Tensile strength decreases by 8%, Flexural strength decreases by 8% and Impact strength reduced by 55% [4].

For GF/PEEK, Tensile strength decreases by 10%, Flexural strength decreases by 9% and Impact strength reduced by 68% [4].

For PLA also, when increasing the printing speed tensile strength increases because there was stronger bonding between layers due to shorter time gaps between successive layers at high print speed [6].

The increasing of printing speed increases the strength up to 90mm/s but when further increased, the tensile strength was reduced [9]. So it is suggested using high values of printing speed but up to a certain limit which can be dependent upon other parameters like material, etc.

4.3 Nozzle temperature:

The effect of nozzle temperature on the PEEK material and its fibre reinforced variants was that when the temperature increases the tensile strength increases. But the CF/PEEK had higher tensile strength than GF/PEEK at same temperature. 5 wt% CF/PEEK achieves max tensile strength of 94 MPa at 440°C (20% higher than pure PEEK). The flexural strength also increased but this time the GF/PEEK had higher value of flexural strength than CF/PEEK at same temperature. At 440°C, 5 wt % GF/PEEK flexural strength exceeds PEEK. But the impact strength decreased which means Fiber-reinforced PEEK composites are less tough. [4]

For PLA printing increasing the extrusion temperature increased dimensional accuracy and also by increasing extrusion temperature, the tensile strength increased because there was better layer fusion at high extrusion temperature which improved strength. Voids and air gaps increase with higher extrusion temperature. [6]

4.4 Infill density:

The infill density refers to how much material is used inside a 3D-printed object. In ABS material, the deviation for corresponding infill density was 4.7% for 20% density, 5.1% for 35% density, 5.49% for 50% density. Which means that increasing the infill density decreases the dimensional accuracy of FDM 3d printing. This happens because higher infill density introduces more molten material in the part, which tends to flow outward [2].

In PLA material, when the infill density increased from 20% to 100%, the Young’s modulus increased from 861.78 MPa to 1538.05 MPa. Which means that increasing the infill density, the strength increases.

V. CONCLUSIONS

- Higher values of layer thickness reduces the strength and accuracy. But on the other hand it is faster than lower values of layer thickness.
- Increasing printing speed under a certain limit increases the strength for PLA and ABS material. But for PEEK and its fibre reinforced variants, strength decreases. It also increases the dimensional accuracy of printed part.
- Increasing the nozzle temperature, increased strength and gave better dimensional accuracy.
- Higher infill density reduces dimensional accuracy but increases strength.
- For ULTEM 9085 material, increasing the contour width, contour number and decreasing the air gap, raster width, increased the tensile strength. But the raster angle had the maximum influence on tensile strength. 0degree raster angle was better than 90 degree.
- Horizontal growing direction had better tensile strength than vertical growing direction.
- Cooling rate had negligible effect on horizontal orientation but for vertical increasing cooling rate decreased strength.
- For many different patterns, linear pattern had best and hexagonal pattern had worse strength.
- The CFR-PLA had maximum and pure ABS had minimum value of Young’s modulus, bulk modulus and flexural modulus.

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