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Exploring the Impact of Process Parameters on 3D Printing: A Comprehensive Review for Enhanced Product Quality

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Abstract

Rapid developments in 3D printing technology have dramatically changed a wide range of industries, from consumer products and healthcare to automotive and aerospace. 3D printing is a process of manufacturing where material is deposited layer over layer which are previously deposited to provide the design shape to the desired products. This process has eliminated the numerous machining processes which were required to manufacture the products previously. The modification of process parameters during printing is a significant element influencing the performance and quality of 3D printed products. This in-depth review study seeks to investigate and evaluate how different process parameters distress the general effectiveness, precision of 3D printing. We look at how factors like height of layer, speed of printing, and setting of temperature, infill density, material characteristics, and more affect the final product. We provide insightful information for academics, engineers, and practitioners to successfully optimize their 3D printing processes and obtain improved results by synthesizing findings from many studies and trials. This review paper's major goal is to provide an in-depth description of recent research on improved statistical and experimental design approaches for printed components made of various materials, including PLA, ABS, PET-G, and others, as well as how manufacturing parameters influence surface quality and tensile strength.

Keywords: 3D printer, additive manufacturing, process parameters, PLA, ABS etc.

INTRODUCTION

Boumedine et al., 2023, the most common and commonly utilized method is "additive manufacturing" (AM), which is also famous as 3D printing [1]. Shanmugam et al., 2021, the components were built layer by layer using additive manufacturing and direct material deposition using CAD file data. The most widely used AM technology at the moment is fused deposition modelling (FDM) [2]. Giri et al., 2021 a plastic filament is melted during production and then instantly placed on a flat surface to make a solid object [3]. Rajpurohit& Dave, 2018 fused deposition modeling's primary benefits stem from its inexpensive cost in consumable materials and equipment as well as its straightforward process parameters [4].

Mohan S, et al., A number of variables, including the printer's specifications, process variables, and post-processing procedures, affect the mechanical qualities of parts produced by 3D printing [5].

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Gibson & Rosen, Making a 3D digital model of the item you wish to print is the first stage in the printing process. You can do this by using CAD software or by utilizing previous 3D models from web repositories. After creation, the 3D model needs to be separated into thin horizontal layers. This process is managed by slicing software. The slicing software generates a set of advice called G- code that instructs how each layer should be produced by the 3D printer. Before printing, the 3D printer needs to be configured [6]. Rismalia et al., 2019 (a), this entails calibrating the printer properly, feeding the filament material (such as PLA or ABS) into the extruder, and levelling the build plate to ensure proper adhesion of the first layer [7]. The 3D printer begins printing after the setup is complete. The printer's nozzle heats the filament until it melts and the molten substance is then ejected through the nozzle. In order to deposit the melted material layer by layer, the nozzle travels along the X, Y, and Z axes as directed by the G-code. As each layer solidifies and cools, it joins with the one before it. The material rapidly cools and solidifies during the deposition of each layer, forming a firm link between them. Some 3D printers come equipped with heated build chambers that help to keep the temperature steady and lower the possibility of warping or delamination. Support Structures (Optional): The slicing programmer may automatically construct support structures if the object has overhangs or complex shapes. These fictitious constructions serve as a basis for the layers above and can be taken down after printing is finished. When the printing is finished, the 3D printer is switched off, and the produced object is taken out. As shown in the given Figure1. If there were any support structures, they are taken down, and if further processing is required, such as sanding or painting, it can be done.

Therefore, reviewing the literature on how process parameters impact the mechanical properties of various materials, including PLA, PLA+, PLACF, ABS, and PETG specimens printed using various processes, including FFF and FDM, is the primary goal of this research project. To ascertain the impact of various process factors on mechanical quality, statistical methods such as the "Taguchi method", "Design of Experiment" (DOE), and "Analysis of Variance" (ANOVA) were employed. With the correct practice variables, the enhanced 3D printed items can be printed with more accuracy and better finishing quality.

PROCESS PARAMETERS

Process parameters in 3D printing relate to the many options and controls that may be changed during the printing procedure to regulate the properties and caliber of the manufactured item. Sivasubramanian Palanisamy et al. These factors are vital in achieving the intended print quality and performance since they have a major impact on the outcome. The important process variables that are frequently seen in 3D printing are given below in Figure 2 [8].

The precision, efficiency, and properties of the 3D printed goods are greatly affected by the predetermined practice variables of the FDM technology. To keep things simple, the process parameters are basically separated into three macro classes: process-based, geometry-based, and structural. The categories are Filament size and Nozzle size, again depending on geometry. Parnika Shrivastava, Anil Dhanola et al. Additional process-dependent categories include printing speed, bed temperature, and printing temperature, Raster angle, raster gap, raster width, number of layers, layer thickness, infill pattern, etc. [9–10]. Process-based and structurally-based process parameters were the main focus of this study. Prabhakar et al., 2020 to understand the impact of various process factors and their relationships in the current period, a thorough review of previously published research is crucial.

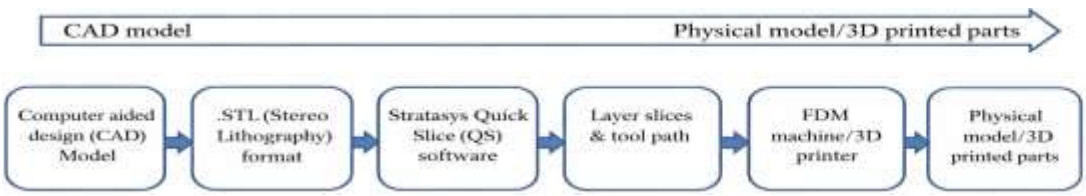

Figure 1. Basic steps involved in FDM Process [8].

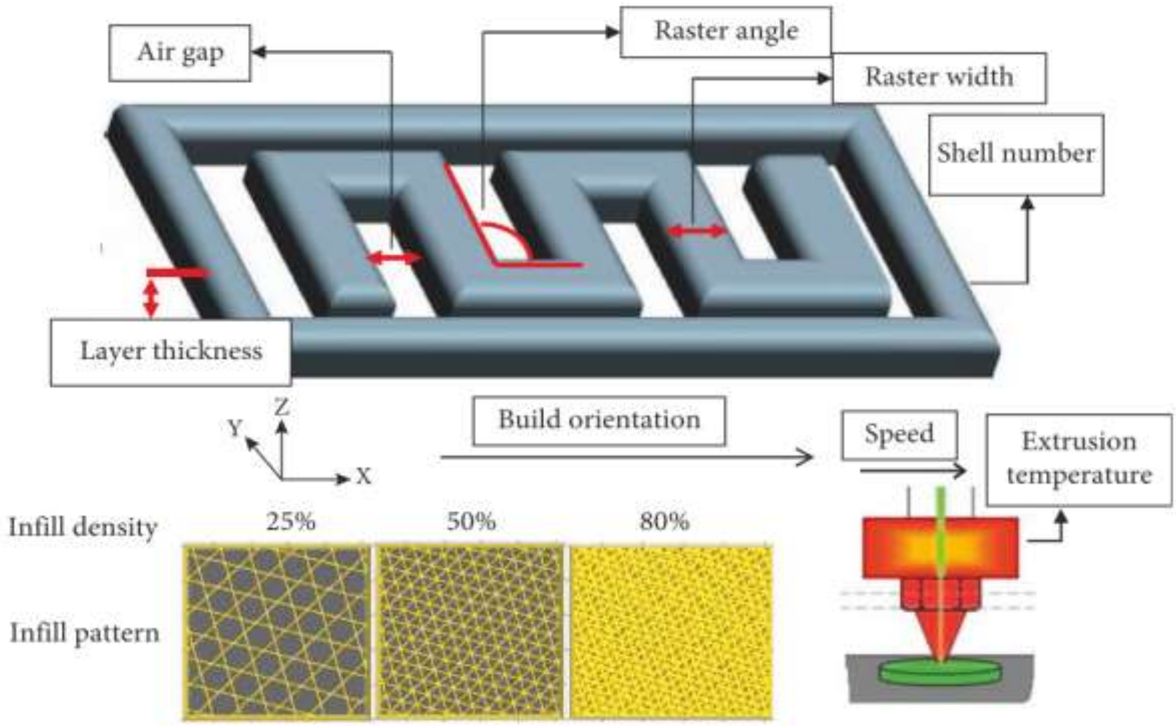

Figure 2. Diagrammatically depiction of various practice variables of 3D printing [11].

To get the desired qualities of 3D printed parts; numerous researchers examined a variety of controllable process parameters [11]. They observed that a number of adjustable practice variables had an impact on the mechanical qualities of 3D printed items. Fuzzy logic, evolutionary algorithms, artificial neural networks (ANN), response surface methodology (RSM), Grey relation and other optimization techniques were used by the researcher to optimize process parameters.

NOZZLE TEMPERATURE

The temperature at which a rigid filament becomes a liquid that may be extruded is known as the extruder temperature. Since the temperature of each plastic filament varies, this temperature must be attained for printing to be done correctly. Certain filaments needed a certain heated bed temperature in addition to a defined extrusion temperature as discussed in Table No.1 (Table 1: Summary of a survey of past articles on nozzle temperature). A heated bed also improves adhesion, which is necessary to guarantee that the first layer sticks properly and that the printed portions do not come away from the bed during printing. PLA is the most popular filament today, due to its leniency with printing condition. PLA print best at around 210ºC, the range for PLA nozzle temperature is 180–230ºC and bed temperature is 60ºC.

ABS required slightly higher temperature to print a part successfully at 230ºC. Nozzle Temperature range for ABS is 210–250ºC and bed temperature is 80–110ºC. PETG required high temperature, the nozzle temperature range between 220-250ºC and bed temperature between 50-75ºC. Nylon is another incredibly powerful filament, it prints at temperature hotter than any other filament, nozzle temperature range 240–260ºC and the bed temperature is 70–100ºC. TPU is a flexible filament, TPU prints at similar temperature to PLA around 210–230ºC with a bed temperature between 30–60ºC. Chad Duty et al. this research work focused on the framework for extrusion-based printing and a simple viscoelastic model for each of these conditions based on the rheological and thermo-physical properties of the candidate material and the processing parameters of the extrusion-based deposition platform.

Table 1. Summary of a survey of past articles on nozzle temperature in the literature

Material	Process parameter taken into account	Method/technique considered	Mechanical characteristics	Analysis/results	References
Wax3D filament	Nozzle temperature, Layer thickness, Extrusion velocity,	Taguchi orthogonal array	Thermal, Mechanical, and rheological characterization	Comparing Wax3D to common 3D printed polymers like PLA and ABS, you can see that it is substantially less elastic and has a lower Young's modulus.	[14]
TCP–PLA composite filament	Nozzle temperature	ANOVA T-test	Rheological properties Tensile Strength	The PLA showed higher tensile strength than the TCP-PLA at all nozzle temperatures.	[15]
PLA+	Nozzle temperature, Layer Height, Print Speed	Taguchi Method	Gray Relational Analysis	Proposes ideal configurations for process parameters. In particular, layer height is 0.10 mm. Print Temperature: 220°C; Print Speed: 30 mm/s.	[16]
PLA	Nozzle temperature, Filling percentages	MET-DHG-D Shore D hardness test	Tensile, Shore D hardness, and Young's modulus testing	As the percentage of infill increased, so did the Young's modulus value.	[18]
PLA and PLA-copper materials	Infill pattern, print density, print temperature, and print speed.	Analysis of Variance (ANOVA)	Tensile Strength	The PLA-Copper print yields the highest tensile force when it is printed at 185°C, 75% infill density, and 65 mm/s.	[21]
PLA	temperatures, raster angles, and layer thickness	Taguchi and Response Surface Methods	Dimension error test and tensile strength	A high-quality printed part was produced using the RSM's optimum parameter settings of 0.05 mm, 199.8 ºC, and 45.1º.	[22]
LW-PLA	Nozzle Temperature	Analysis of variance (ANOVA)	Mechanical strength	The mechanical strength decreased by 65% when the extrusion nozzle's temperature was raised from 210 to 250 °C.	[13]

The strength between printed layers is significantly affected by the material's viscoelastic behavior. Materials that exhibit suitable viscoelastic characteristics can form stronger interlayer bonds, leading to improved mechanical properties in the final printed object [12]. Freitas et al. 2023, Research looked at the effects of changing printing nozzle temperature on a low-density poly-lactic acid material's mechanical properties and dimensional accuracy. It was observed that density decrease with increase the extrusion nozzle temperature. Mechanical strength of printed parts also decreases with increases the temperature [13]. Mukhtarkhanov et al., 2022 was focused on how process variables affected the mechanical, thermal, and rheological qualities of printed items. The main process parameter of this research was nozzle temperature.

To optimization of results Taguchi orthogonal array process was used. Wax filament material was used for cost-effective investment casting patterns. Layer thickness and printing temperature were the two factors that had the greatest impact on dimensional accuracy [14]. Elhattab et al., 2022centered on how the four nozzle temperature settings (190, 200, 210, and 220 degrees Celsius) affected the mechanical and rheological properties of the β-Tricalcium Phosphate and Ploy lattice composite filament. It was shown that the crystallinity of printed PLA and TCP-PLA components was improved by an increased nozzle temperature in the FDM process [15]. Arifin et al., 2021, explore the effects of printer practice variables on the hardness and shrinkage of 3D printed PLA+ objects, such as layer height, temperature, and print speed. Three distinct levels of each process parameter are used by the researcher in this work. The three nozzle temperature levels are 210, 215, and 220 degrees Celsius. GRA and Taguchi method are used to examine the collected data [16].

Hsueh, Lai, Wang, et al., 2021, concentrated on the effects of process variables on the thermal (thermal deformation) and mechanical (tension, compression, and bending) characteristics of 3D printed items composed of polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) materials. The researcher consider two process parameter such as printing temperature (180–210^{o}C for PLA and 215-230^{o}C for PETG) and printing speed (45, 40, 35 mm/s for PLA and 35, 30, 25 mm/s for PETG). The mechanical characteristics of PLA and PETG material printed parts (tension, compression, and bending) were found to be enhanced at higher printing temperatures [17].

Hsueh, Lai, Wang, et al., 2021, The current research examined the effects of two process parameters printing temperature and filling percentage on the mechanical characteristics of poly-lactic acid material, specifically its ultimate tensile strength, young's modulus, and shore hardness. The researchers consider four levels of infill such as 10%, 20%, 33.3% and 50% and five levels of printing temperature 185^{o}C, 195^{o}C, 205^{o}C, 215^{o}C, 225^{o}C. Compliance to ASTM D-638, a tensile test was conducted, and the findings reveal that raising the printing temperature can significantly increase the material's shore hardness, elongation, ultimate tensile strength, and tensile young's modulus [18]. Tho NH et al., 2020, investigated how a process parameter affects the tensile strength of regular PLA and PLA-Copper fabricate specimens.

The main process parameters used in this work were as follows: printing speed (50, 65, and 80 mm/s), printing temperature (175, 185, and 205^{o} C), infill pattern (linear, grid, tri-hexagonal), and infill density (20%, 50%, and 75%). To find out how a process parameter affects the tensile strength, ANOVA was employed. The results show that the ideal printing parameters for tensile force were 75% infill density, 65 mm/s [19]. A.E et al., 2017, investigated how process variables impact the tensile strength and dimension error test results for PLA filament standard specimens (ASTM D638 type IV) was the aim of this investigation. Layer height (0.05, 0.1, and 0.15), print temperature (195, 200, and 205 degrees Celsius), and raster angle (-45, 0, and 60 degrees) were among the process factors used. For the best outcomes, Taguchi and the Response Surface Method (RSM) technique were applied. The results indicate that the process parameters of layer height 0.1 mm and temperature 200^{o} C with 0^{o} orientation were optimized [20].

Table 2. Summary of the literature review of previous attempts on the infill pattern

Material used	Process parameter taken into account	Method/technique considered	Mechanical characteristics taken into account	Analysis/results	References
PLA	triangles, cubic, concentric, tetrahedral, lines, and zigzag	Experimental modal analysis	Flexural strength Elastic Modulus and Natural frequencies	The maximum flexural stress for the cubic infill pattern with edgewise orientation is 107.95 Mpa.	[5]
PLA	Gyroid, Rhombile, circular, truncated octahedron, and honeycomb	ANSYS	Universal Testing Machine	The hexagonal infill design has exceptional mechanical qualities.	[27]
PLA, Tough PLA and Polycarbonate	Triangles, Octets, Quarter Cubic's, Grid, Tri-Hexagon, and Cubic Subdivision	Universal testing machine	Elastic modulus and tensile force	Strong PC material with infill structure tensile strength fluctuations of up to 6% and tough PLA material with changes of up to 10%	[28]
PLA	Rectilinear, Honeycomb, Triangle and Grid	ANOVA and Turkey's test	Impact resistance and tensile strength	The best performance was demonstrated by the rectilinear design, which had a high tensile strength, resistance to impact, and an elastic modulus.	[29]
PLA	Grid, triangle, triangular, and cubic quarters	The compression test and low-velocity test for impact	Toughness, stiffness and strength	Peak force of 1190.5N was achieved for the triangle pattern.	[30]
PLA and Cpla	Concentric, zig zag and grid	Tensile test & Vickers test	Tensile strength &micro hardness	The best tensile strength of PLA is found with zigzag infill patterns. The strongest cpla is that which has a grid design.	[31]
Lightweight cellular PLA	Hexagonal, Tri-angular, Square, Square-diagonal, Reinforced Square-diagonal	Uniaxial Tensile testing	Stiffness and Strength	The projected best mechanical performance was displayed by the square infill pattern.	[33]
PLA	Hexagonal, Grid and Triangle	Universal Testing System	Highest tensile strength and the Young's modulus	The hexagonal infill design continuously showed the best Ultimate Tensile Strength.	[25]
PLA	Honeycomb and Grid infill	Zwick Roell Z100 Tensile Test Machine	Young's modulus, ultimate tensile strength,	Young's modulus appears to be constant regardless of the tested strut thickness.	[26]

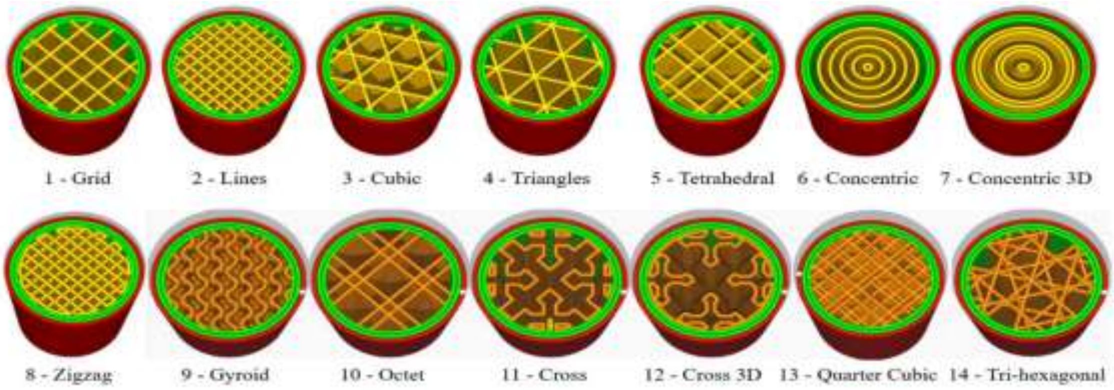

Figure 3. The fourteen infill patterns [24]

INFILL PATTERN& INFILL DENSITY

Infill pattern

The process of printing an inner structure into a component is known as an infill pattern. Infill designs come in a wide variety thanks to 3D printing as shown in Figure 3 and Table 2 (Table 2: Summary of the literature review of previous attempts on the infill pattern) discussed about the various infill patterns used by researchers.

The number of alternative infill patterns varies according on the slicer software used, such as Cura, Simplify 3D, and Prusa Slicer 2.4.0, which has 16 of them. Solomon et al., 2020, for superior mechanical qualities, the most common infill patterns include linear, honeycomb, cubic, hexagonal, etc. This is because the tensile and compressive characteristics of printed items may vary depending on the infill pattern used. The weight and printing time of printed parts are also impacted by infill patterns [23].

Khaliq et al. 2023 the impact of multiple infill patterns, including Grid, Hexagonal, and Triangle, with various infill densities (25, 50%, and 75%) on the mechanical properties of printed parts composed of poly-lactic acid (PLA) materials, is being examined by the researcher [25]. Birosz et al. 2023, researcher focused on the effect of infill scaling technique to evaluate the effectiveness through mechanical properties. By properly modifying the infill pattern size, the print time can be decreased to some level. Here two infill pattern Honeycomb and grid with four level of strut thickness 12, 16, 20 and 24mm was used [26]. Mohan & Student, 2022, evaluating the impacts of build orientations and infill patterns on the mechanical integrity of PLA material was the main goal of this work. Six potential infill designs triangles, cubic, concentric, tetrahedral, lines, and zigzag as well as three specific orientations were investigated by the researchers using rectangular beam-type components.

The mechanical properties of products with a variety of infill patterns and orientations are assessed using flexural bending tests [5]. Ganeshkumar et al., 2022, was focused on investigation of the mechanical properties (Fracture and Yield Strength) of specimens ASTM D628 standard for tensile test. For PLA buildings, five alternative infill patterns, including gyroid, rhombic, circular, truncated octahedron, and honeycomb infill, were used [27]. Pandzic & Hodzic, 2021, examined how varied infill patterns affected the tensile characteristics of poly lattice acid (PLA), tough PLA, and PC materials. Cura slicer was used to create material testing specimens in accordance with ISO 527-2 standard. The influence mechanical behavior of all materials is discovered by statistical analysis of all outcomes [28]. Cabreira & Santana, 2020, used fused filament fabrication (FFF) to examine how infill patterns affect the tensile strength and impact resistance of poly-lactic acid (PLA) material. In this study, four infill patterns were employed. A standard specimen ASTM D526 was utilized for Izod testing, while a standard specimen ASTM D 638 was used for the tensile test [29]. Aloyaydi et al., 2020, this study looked at how the mechanical response of 3D-printed items was impacted by the infill pattern. Four different infill schemes were used to generate the test specimens: quarter cubic, tri-hexagon, triangle, and grid. It was put through a compression test and a low-velocity impact test (LVI) to get the mechanical responses (Toughness, stiffness and strength) [30].

Yeoh et al., 2020**,** in this work, the mechanical characteristics of printed objects are investigated in connection with the infill pattern. PLA and CPLA materials were used with three different infill patterns with 80% infill solidity. Tensile test (ASTM D638) and Micro-hardness Vickers test (ASTM E 384) was conducted to get best results [31]. Schmitt et al., 2020, this study examined how process variables affected the mechanical characteristics of the parts that were made from acrylonitrile butadiene's (ABS). Six different infill patterns (solid, single dense, double dense, hexagonal, triangular and sawtooth) were utilized for uniaxial tensile test and 3 point flexural specimens (ASTM D790-02). Nikon SMZ745 optical microscope was used for examination of infill configuration [32]. Lubombo & Huneault, 2018 this research investigates the mechanical properties (strength and stiffness) of lightweight PLA material made by FFF process. The cellular parts were printed with one and three perimeter shell with distinct infill patterns: square, square diagonal, reinforced square diagonal, hexagonal, and triangular [33].

Infill Density

The infill density is the quantity of material deposited on the specified elements as shown in Figure 4. Solomon et al., 2020 infill densities of printed parts directly influence the properties of printed components. Lesser density means lesser the mechanical properties as compare with denser components. It is found that the infill pattern has no more of an impact on mechanical properties at 100% infill density [34]. Table No.3 (Table 3: Summary of review of earlier works of literature regarding Infill Density) discussed the most advantageous mechanical characteristics include fully infilled density when build time is not a concern.

Liu et al., 2022, improving the mechanical properties of asymmetrical items with different cross-sections was the aim of this work. An adaptive density filling framework was suggested. The Hilbert curve infill pattern was used to fill the sample's infill density. Compared to the larger cross-section, the smaller cross-section has a higher infill density. Three-point bending, dynamic compression testing, and quasi-static compression were used to determine the printed PLA and ABS specimens' ultimate bearing capacity [35]. Pandzic et al., 2021 this study's primary objective was to determine the effects of infill densities of 20%, 60%, 80%, and 100% on the mechanical characteristics (Elastic and Tensile Modulus) of strong PLA, ABS-X 3D printed materials, and PLA antibacterial nano composite [36]. Naik & Thakur, 2021 the impact strength and impact strength/weight ratios were the main topics of this study by process parameter of Bio-inspired Poly-lactic Acid (PLA) material. The researcher used five levels of infill density (100%, 80%, 65%, 35%, and 20%) and two type of print orientation (flat and on-edge) with multi infill patterns (honeycomb, grid and triangular infill). A turtle shell or similar bio-inspired construction used as the model for the ASTM D256 test specimen. IT 503 Izod impact tester was used for Izod strength and Strength/weight ratio [37]. Tanoto et al., 2021 the primary purpose of this study was to look at how process parameters affected the Flexural strength of high impact polystyrene (HIPS) material. Combined Deposition

Figure4. Infill density of 20%, 40%, 60%, 80% and 100% [24].

Table 3. Summary of review of earlier works of literature regarding infill density.

Material used	parameter taken into account	Method/technique considered	Mechanical characteristics taken into account	Analysis/results	References
PLA and ABS	Hilbert curve infill pattern	3-Point bending	Bending & Dynamic compression tests	The connection between bearing capacity and infill density	[35]
ABS-X, tough PLA (tPLA), and PLA nano copper composite (cPLA).	20%, 60%, 80% and 100%	Universal Testing Machine	tensile strength, elastic modulus	In objects with 100% infill solidity, the cPLA material's maximum tensile strength is 21 5% greater than that of tPLA and 45.6% greater than that of ABS-X.	[36]
PLA	Grid infill, triangular, and honeycomb with 20%, 35%, 50%, 65%, 80%, and 100%	Izod impact Testing	Izod strength and weight-to-strength ratio	The specimen constructed with a 20% infill density had the highest impact strength and impact strength/weight ratio.	[37]
High impact Polystyrene (HIPS)	patterns of hexagonal, lattice, and linear fill with 25%, 50%, and 75%	Analysis of variance (ANOVA) &Taguchi	Flexural Strength	Orientation position 3, a lattice fill pattern, a 75% fill density, and a 0.125 mm layer thickness yield the highest flexural strength.	[38]
PLA and PLA-copper materials.	20%, 50%, & 75%	Analysis of Variance (ANOVA),DOE	Tensile strength & S/N (signal/noise) ratio	The optimal parameters for PLA-Copper material result in an infill density of 75% for the maximum tensile force.	[39]
Polylactic Acid, and Carbon fiber filaments	60%, 70%, 80%, 90%, and 100%	Universal Testing Machine	Variable printing density's impact on mechanical properties	Since carbon fiber is more ductile than PLA, it suggests that failure will occur.	[40]
Polylactic acid (PLA)	20%, 35%, 50%, 65%, and 80%	Impact test	Impact strength and Fracture toughness	A higher impact test value is produced by increasing infill density, which	[41]
Polyethylene terephthalate glycol with polylactic acid	10%, 20%, 33.3% and 50%	QC-H51A2 universal testing machine&QC-654 heat deflection tester	Tension, Compression, Bending, and Thermal Deformation	PLA has better mechanical qualities than PETG does.	[42]

The following modelling parameter was used: - print orientation, including layer height (0.125, 0.25, and 0.5 mm), infill pattern (lattice, linear, and hexagonal), and perpendicular bed height, width, and length. The Taguchi method's experimental design (DOE) was utilized to optimize a process parameter [38]. Tho NH et al., 2020 the impact of process parameters on the tensile strength of printed PLA and PLA-Copper standard specimens is examined in this study. The following were the main process parameters used in this investigation: Linear, grid, and tri-hexagonal infill patterns; infill densities of 20%, 50%, and 75%; printing speeds of 50, 65, and 80 mm/s; and printing temperatures of 175, 185, and 205 degrees Celsius. An analysis of variance (ANOVA) was utilized to assess and identify tensile strength by determining the impact of a process parameter [39]. Soud et al., 2019 the purpose of this research was to determine how infill density affects the mechanical characteristics of test specimens made of carbon fiber (CF) and polylactic acid (PLA). Test specimen was fabricated by six level of infill density (10, 30, 50, 70, 90 and 100%) to test tensile strength. Stress strain diagram of PLA and CF material of varying density was studied [40].

Ali, 2018 investigated and assess how infill density affects the impact strength and fracture toughness of specimens that were printed using PLA. Impact specimens were tested with five levels of infill density (20, 35, 50, 65, and 80%), and it was discovered that the impact strength and toughness are dependent on the infill density [41]. Hsueh, Lai, Liu, et al., 2021, this study examined how two process parameters printing temperature and filling percentage affect the mechanical characteristics of polylactic acid material, specifically its ultimate tensile strength, young's modulus, and shore hardness. Four infill levels 10%, 20%, 33.3%, and 50% as well as five printing temperature levels 185, 195, 205, 215, and 225 degrees Celsius—were taken into consideration by the researcher. ASTM D-638 was followed for performing the tensile test [42].

INFILL PATTERN AND DENSITY

Pernet et al., 2022, understanding the mechanical qualities was the primary goal of this study. Compression Test and life cycle cost assessment test of ASTM D695 standard cylinders for fourteen different infill patterns of 3D printed parts of Poly-lattice Acid material. An Instron test platform was used for compression testing, which were used to compare the weight and stress relationships of each building [24]. Qamar Tanveer et al., 2022, the primary goal of this study was to provide a concise summary of AM techniques, with a focus on FDM and related process factors. Determining the impact of infill solidity and pattern on the performance of 3D printed goods was the main goal of the study [21]. Triawan et al., 2022, this study looks at how 3D printing variables, i.e. infill density and pattern selection, affect the mechanical and fracture performance of 3D printed structures. The mechanical behaviors of the specimens were tested using the tensile test technique and analytical inspection. Additionally, this analysis shows that the influence of the infill pattern will be lessened if the infill density is around 100% [22].

Hodzic & Pandzic, 2021, the foremost goal of this study was to examine the effects of several infill patterns, including concentric, grid, gyroid, octet, and triangular, with variations in density at five different levels (20%, 40%, 60%, 80%, and 100%) for each design. Standard specimens were used to test the PLA FDM printed material's compressive strength, flexural strength, and elastic modulus. ASTM D695 was used for the compressive strength specimen, while EN ISO 178 was used for the flexural strength specimen [43]. Bonada et al., 2021, finding the impact of infill patterns—specifically, grid, linear with a raster orientation between 0 and 90, and linear with a 45-degree raster orientation—on the mechanical characteristics (Poisson ratio, elastic modulus, and tensile test) of 3D printed parts using FFF was the primary goal of the study.

The Young Modulus and Poisson Ratio of printed parts were compared using the Representative Volume Model (RVE) technique. The findings unequivocally demonstrate the variations in mechanical characteristics, even when comparable 3D printing parameters were employed [44]. Jasim et al., 2022 this study examines the effects of various infill patterns on the tensile strength of test specimens made of PLA material. In addition to the subdivisions of zigzag, gyroid, concentrated, octet, and cubic, ten other infill patterns were employed as process variables, including the tri-hexagon, lines, triangles, grid, and cubic. Using the standard tensile test specimen in accordance with ASTM D638 and this printing parameter, the tensile strength was determined [45]. Dezaki et al., 2021, comparing sections of PLA material produced by fused deposition modelling (FDM) with computer-aided design (CAD) models was the primary objective of this study. To assess the results, surface roughness and tensile strength measurements were conducted on the dog-bone sample.

Four distinct infill patterns with various infill densities made up the sample. FEA was conducted to judge against the printing and simulation practices [46]. Mishra et al., 2021, the researcher focused on experimental investigation on polylactic acid (PLA) specimens (ASTM D 256) through Izod impact test. 3D printed parts have combined effects of the specimen's infill density and infill pattern. The researcher used 12 infill pattern and out of these 12 infill 9 infill patterns used in two infill density (50% and 70%) rest three (zig-zag, line, concentric) infill patterns were used seven level of infill density (50%, 75%, 80%, 85%, 90%, 95% and 100%) [47].

Martulli et al., 2021, the impact of process variables on the flexural stiffness and elastic properties of onyx fused filament fabricated (FFF) sections a specimen that resembles a sandwich beam is examined in this study. For the test specimens in this study, three distinct infill patterns rectangular, hexagonal, and triangular with infill densities of 40%, 60%, and 80% were employed [48]. Ma et al., 2021, this study investigates various process parameters affect the quasi-static axial compression stress on 3D printed objects composed of materials such as PLA and PLA+CF. There were four levels of infill density (20, 40, 60, and 80%) and four infill patterns (20, 40, 60, and rectilinear).

Prusa I3 MK printer created the test sample (cubes) [49]. Wang et al., 2020, this research systematically investigates the mechanical properties (elasto-plastic deformation and failure behavior) as a function of process variables (infill density, infill patterns, and strain rate) of polyamide-based composite (Onyx) material specimen. A digital camera (RX100M6, SONY Co.) and a UTM-E44.304, MTS Co., Eden Paraire, MN, USA) were used to perform a tensile test on a standard specimen [50]. Rebenaque & González-Requena, 2019 the primary goal of this study was to analyze the effect of process parameter on flexural strength of printed specimen through FDM technique.

Three infill pattern with three level of infill density (30, 50 and 80%) was used. 3 point flexure test was conducted on Test specimen (UNE-EN ISO 178(2011)) [51]. Rismalia et al., 2019, the link between mechanical characteristics and process parameters (infill density and infill pattern) was the main focus of the study. PLA-based standard tensile test specimens were produced in compliance with ASTM D638. Three infill patterns (grid, tri-hexagon, and concentric) and three infill density levels (25, 50, and 75%) were used to create a finite element model (FEM) for the best results [52]. Baig et al., 2019, the main purpose of the study was to explore how process parameters (infill pattern and infill density) affected the mechanical behavior of printed parts using PLA material and three infill patterns (triangular, hexagonal, and linear) with three levels of infill density (25, 50, and 100%) [53]. Bogrekci et al., 2019, this study's primary goal was to find out how the density and pattern of infill affected the hardness of PLA pieces that were created.

There are seven distinct infill patterns with varying infill densities (15, 25, 50, 75, and 100%): honeycomb, line, concentric, rectilinear, Hilbert curve, Archimedean chords, and Octagram spiral. The Vickers and Knoop hardness test was carried out using the Durascan EMCO test [54]. Fernandez-Vicente et al., 2016, this study examines how densities and infill patterns affect the tensile strength of ABS items that are 3D printed. For the standard specimen (ASTM D3039), three infill patterns (Honeycomb, line, and rectilinear) with infill densities of 25, 50, and 100% were utilized. The results indicate that the impact of infill solidity on tensile strength is highest and the impact of infill pattern is only 5% [55].

BUILD ORIENTATION

In 3D printing, "build orientation" refers to how the 3D model or object is orientated on the build platform throughout the printing process as shown in Figure 5. The final print's mechanical properties, functionality, and quality can all be strongly impacted by the object's placement. The build orientation needs to be done correctly in order to achieve the desired results and avoid any issues throughout the 3D printing process.

One of the most important variables that might impact the FDM/3D printing process's build time, support material quantity, shrinkage, distortions, resin flow, material cost, and support volume need is build orientation. For homogeneous and standard parts, choosing a build orientation could be straightforward (Matos et al., 2020). This research area examines a variety of literature on construction orientation and how it affects mechanical qualities.

Zhen et al. 2023: The researcher looked into how the mechanical responses of PEEK-made 3D printed objects were affected by the extrusion rate, filling angle, and print orientation. The experiments also focused on the heat treatment parameters to modify the material's strength and crystallinity. The results indicate that the strength is over 80% more than that of PEEK injection-molded components [57]. Alzyod & Ficzere, 2022, this research work investigates the effect of layer orientation (continuous horizontal, continuous vertical, horizontal orientation with a pause, vertical orientation with a pause) on the tensile strength of PLA fabricated items using the fused deposition modelling approach on Prusa i3 MK3S. Both horizontal printing in both directions had no effect, according to experimental and statistical analysis, while other printing techniques showed a substantial difference [58].Pandzic, 2021, the study's main focus was on the experimental analysis of the inducement of layer height (25, 50,100,160 microns), build orientation (vertical, side and flat) and post curing (30 min, 60 °C) on mechanical properties (tensile strength) of stereo lithography SLA 3D printed Grey Resin material. The standard specimens of ISO 527-2 were used at universal testing machine Shimadzu AGS-X for analysis of material [59].

Tanoto et al., 2021, the study's primary goal was to examine how process parameters affected the Flexural strength of high impact polystyrene (HIPS) material. Combined Deposition The following modelling parameter was used: - print orientation, including layer height (0.125, 0.25, and 0.5mm), infill pattern (lattice, linear, and hexagonal), and perpendicular bed height, width, and length. The Taguchi method's experimental design (DOE) was utilized to optimize a practice parameter [38].Valean et al., 2020, this research work investigates the impact of practice parameter on tensile characteristics of fabricated specimens of polylactic acid (PLA) material.

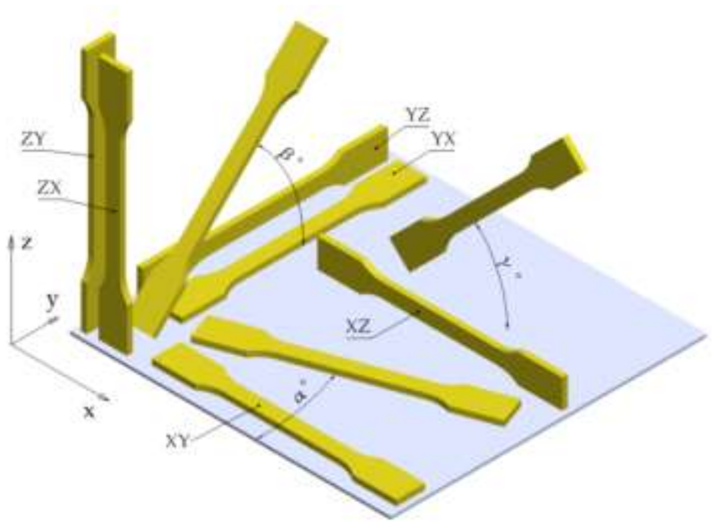

Figure 5. Different build orientations are mentioned according to ISO/ASTM 52921 [56]

The researcher main focus on two process parameter in this research, First parameter was print orientation (0, 45 and 90º) and second parameter was layer thickness (1.25, 2.50, 3.70, 4.0 and 8.0) [60]. Yao et al., 2020this study investigates how the print angle and layer height affect the specimens' mechanical failure strength following fused deposition modelling (FDM) using PLA.Three layer thickness levels (0.1, 0.2, and 0.3 mm) and seven print angle levels (0, 15, 30, 45, 60, 75, and 90o) were employed in this investigation. The ISO 527-2-2012 standard was followed by the test subject [61]. Dezaki & Mohd Ariffin, 2020, this study evaluates how print orientation and infill pattern affect the mechanical characteristics (tensile strength analysis) of an FDM-fabricated polylactic acid sample. Seven distinct build orientations (0, 15, 30, 45, 60, 75, and 90o) were combined with five infill patterns: honeycomb, wiggle, grid, rectilinear, and solid. Finite element analysis was used to optimize the outcomes (FEA) [62]. Kain et al., 2020, the material parameters of a standard test specimen created using the fused layer modelling (FLM) process are examined in this work in relation to the impacts of infill orientation (built orientation).

PLA polymer was used to print samples with two distinct wood fibre compositions (ARBOCEL C100). The impacts of seven different infill orientations (0, 15, 30, 45, 60, 75, and 90o) were investigated on a variety of material properties [63]. Ferreira et al., 2017, finding out how construction orientation impacted the micrography and characterization of 3D printed PLA and PLA reinforced (PLA+CF) components was the aim of this study. Only five specimens with three levels of constructed orientation (0o, 90 o, and +/ 45 o) that were unidirectional or specifically orientated were evaluated. SEM was utilized to inspect the fracture surface of the specimen [64].

LAYER THICKNESS

Your object will be manufactured layer by layer with the process of AM recognized as 3D printing. The vertical separation between each printed layer of the object being created is referred to as layer thickness in 3D printing, also known as the Z-axis resolution or slice height as shown in Figure 6. It is one of the crucial practice variables that have a big impact on the 3D printed object's overall functionality, print quality, surface finish, and printing speed. The manufactured component smoothness and degree of detail are directly impacted by the layer thickness, which is defined by the 3D printer's parameters. In additive manufacturing; layer thickness refers to the measurement of the layer height of each additional layer of material. It is referred to as the quantity of material supplied in a single pass down the vertical axis of the FDM. Solomon and colleagues 2020**,** it is a crucial aspect of every 3D printer's technical design. For office or Fablab fused deposition modelling (Ultimaker, Makerbot, etc.), The thickness of the layer varies between 0.10 and 0.33 mm, whereas professional fused deposition modelling for production (Stratasys) has a thickness range between 0.17 and 0.33 mm. The vertical resolution of the Z-axis is primarily determined by layer height. The impact of a 3D printer layer height on the print result also depends on the orientation chosen for printed objects. Layer height also effect the printing time, printing speed and number of layer required.

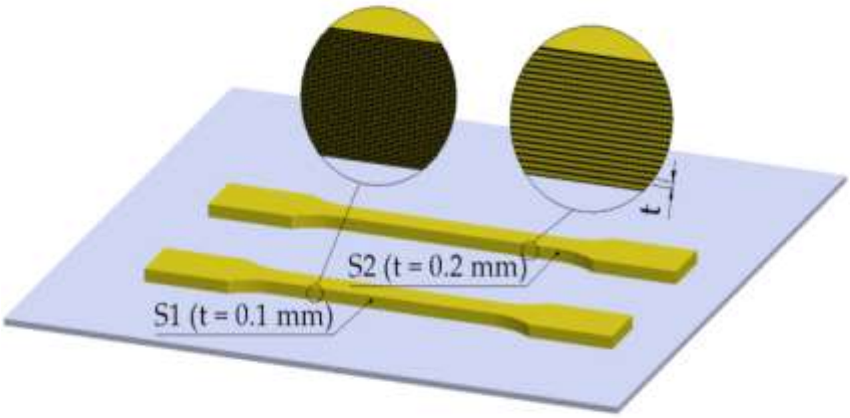

Figure 6. ISO 527-2 tensile specimens (S1, S2), layer thickness (t) [56]

Cojocaru et al., 2022, the study was founded on a methodical examination of the process variables that influenced the mechanical characteristics of Poly-Latice Acid specimens made by FFF [56]. Arifin et al., 2021, examine the effects of printer process variables on the hardness and shrinkage of 3D printed PLA+ products, such as temperature, print speed, and layer height. All process parameters were separated into three tiers for this investigation. GRA and the Taguchi are used to examine the collected data [16].

Farazin & Mohammadimehr, 2022, focused on examining the effects of important 3D printer process factors on the mechanical properties of objects manufactured from PLA. Four levels of infill density—80%, 60%, 40%, and 20% two values of layer thickness 0.1 and 0.2 mm and two levels of printer speed 20 and 40 mm/s were employed in this study. ASTM D-638, a standard specimen, was utilized [65].

Yao et al., 2020, evaluate how the print angle and layer height affect the mechanical failure strength of the PLA specimen made using fused deposition modelling (FDM). Three levels of layer thickness (0.1, 0.2, and 0.3 mm) and seven levels of print angle (0, 15, 30, 45, 60, 75, and 90º) were employed in this study. The testing specimen complied with ISO 527-2-2012 [61]. Tanoto et al., 2021, examine how process parameters affect the high impact polystyrene (HIPS) material's flexural strength. Deposition of Fused The following modelling parameter was used: Print orientation, infill pattern (lattice, linear, and hexagonal), infill density (25%, 50%, and 75%), and layer height (0.125, 0.25, and 0.5 mm) (a perpendicular bed's height, width, and length are its dimensions). The Taguchi method's DOE was employed to optimize the process parameters [38].

Sumalatha et al., 2021, PLA and ABS specimens were made using an AION 500 FDM machine. For the best outcomes, the DOE and ANOVA approaches have been employed. Layer thicknesses were 0.4, 0.3, and 0.2 mm, infill densities were 25, 33.33, and 50%, and print speeds ranged from 40, 55, and 70 mm/s [66]. Ei Ei Cho1, 2019, this study examines how the thickness of the infill pattern layer affects the mechanical characteristics of standard PLA specimens, including as elongation, yield stress, ultimate tensile stress, and Young's modulus. Nine test samples are constructed using three infill patterns (triangles, grid, and zigzag) and three layer thickness levels (0.2, 0.1, and 0.15). The design of experiment (DOE) technique produced the best design and superior outcomes [67].

Rodríguez-Panes et al., 2018, this study examines how manufacturing process parameters affect the mechanical responses of PLA and ABS 3D printed objects using the FDM technique. When compared to PLA material, the ABS outcome displays less variability [69]. Fernandes et al., 2018 the study assesses how process variables affect the mechanical responses of FDM-based PLA, such as elongation, yield strength, modulus of elasticity, and ultimate tensile strength. We look at layer thickness, raster angle, extrusion temperature, and infill density.

Analysis of variance was used to determine the optimal process parameters (ANOVA) [55]. Rajpurohit & Dave, 2018, finding out how a process parameter affects the tensile strength of an FDM printed PLA item in compliance with ASTM D 638 was the aim of the study. Three process factors were used in this investigation: layer height and raster angle (0, 30, 45, 60, and 90o). Between 100 and 300 mm, five different raster widths and layer heights are considered. The maximum tensile strength was achieved at a 0° raster angle [70].

RASTER ANGLE

In 3D printed parts, the raster represents the organization of the succeeding lines in a layer. The raster angle (RA) as shown in Figure 7 affects the anisotropic mechanical conduct and breaking of 3D printed objects. In essence, there are two sorts of raster angles: unidirectional raster, where all subsequent levels maintain the same RA, and alternating raster, where the raster angle changes by 90 degrees between layers. The raster angle, which has a maximum range of 0-90º, is normally calculated with regard to the x-axis.

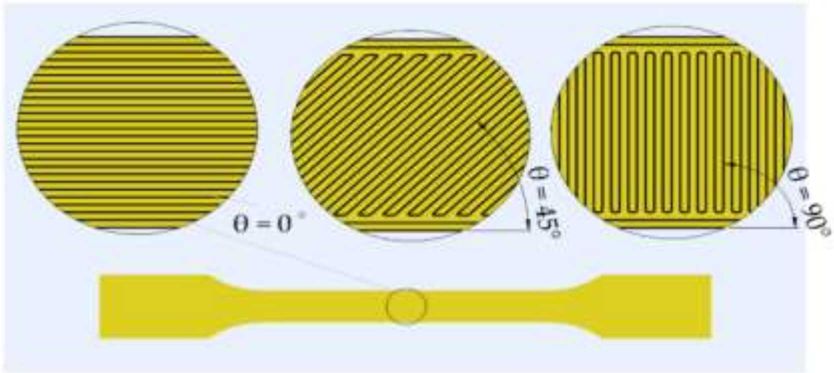

Figure 7. Raster angle (θ) [56]

Cojocaru et al., 2022, the study was founded on a methodical examination of the process variables that influenced the mechanical characteristics of Poly-Latice Acid specimens made by FFF [56]. Sepahi et al., 2021 the purpose of this study was to examine the effects of raster angle on the mechanical properties of three widely used materials: PLA, ABS, and PETG. The 0^o-90^o raster angle of the fracture surfaces results was examined using the SEM technique to reveal brittle and ductile behavior [2]. Rajpurohit & Dave, 2018, the purpose of this study was to examine how a process parameter affected the tensile strength of an FDM printed item in compliance with the PLA material standard (ASTM D 638). RA (0 30, 45, 60, and 90^o), layer height, and raster width were the three process parameters used in this study. At the 0^o Raster angle, the highest tensile strength was recorded [70]. Fernandes et al., 2018, the optimal process parameters were identified through the use of analysis of variance (ANOVA). The mechanical responses of FDM based PLA are examined in this work in relation to process factors (infill density, extrusion temperature, raster angle, and layer thickness) [55]. A.E et al., 2017, this study examines how process parameters affect tensile strength and dimension error test on standard specimen (ASTM D638 type IV) of PLA filament. Process parameters such as Layer height (0.05, 0.1 and 0.15), print temperature (195 ^{o}, 200 ^{o} and 205^{o}C) with raster angle (-45 ^{o}, 0 ^{o} and 60^o) were used. Taguchi and Response Surface Method (RSM) technique were used for optimized results. Result obtained show that layer height 0.1 mm, temperature 200^{o}C with 0 degree orientation were optimized process parameter [65]. Kain et al., 2020, the impact of infill orientation (built orientation) on the material properties of standard test specimens made using the fused layer modelling (FLM) process is examined in this study. PLA polymer was used to print samples using two distinct wood fibre content (ARBOCEL C100) materials. Investigations were conducted on the effects of seven distinct infill orientations (0, 15, 30, 45, 60, 75, and 90^o) on various material qualities [63].

PRINT SPEED

Print speed is the main speed setting that has an impact on your 3D printed items. The printer speed determines how fast the motors in your printer run. It can be defined as the speed at which the developed nozzle traverses the XY plane while depositing material on the constructed platform. The speed at which pieces print is directly related to the printing speed. Faster printing speeds up the manufacturing process, but dimensional precision are compromised. When a fresh layer is deposited, a high printing speed reduces the amount of bottom layer [23]. Hsueh, Lai, Wang, et al., 2021, this study looked into how process variables affected the mechanical (tension, compression, and bending) and thermal (thermal deformation) characteristics of 3D printed polyethylene terephthalate glycol (PETG) and polylactic acid (PLA) parts.

The researcher takes into account two process parameters, including printing speed (45, 40, 35 mm/s for PLA and 35, 30, 25 mm/s for PETG) and temperature (180–210 ^{o}C for PLA and 215-230 ^{o}C for PETG) [42]. Sumalatha et al., 2021, examines how process parameters affect the constructed time and mechanical consideration (impact strength) of printed items. PLA and ABS specimens were made using an AION 500 FDM machine. For the best outcomes, the DOE and ANOVA approaches have been employed. Three levels of print speed (40, 55, and 70 mm/s) were employed together with additional process parameters [68]. Tho et al., 2020, examines how process parameters affect the tensile strength of PLA and PLA-Copper standard specimens that are produced. The following process parameters were employed in this work: - printing temperature (175, 185, and 205 ºC) and speed (50, 65, and 80 mm/s ANOVA was utilized to assess and reveal the impact of process parameters on tensile strength [39]. Farazin & Mohammadimehr, 2022, the primary goal of this study was to examine how key 3D printer process factors affected the mechanical characteristics of manufactured poly-lattice acid (PLA) pieces. Four levels of infill density—80%, 60%, 40%, and 20%—two levels of layer thickness0.1 and 0.2 mm—and two levels of printer speed—20 and 40 mm/s—were employed in this study. ASTM D-638, a standard specimen, was utilized [65].

In 3D printing, print speed is a crucial factor that has a significant impact on the dimensional accuracy and surface finish of printed goods. It was observed from the study that both surface roughness and dimensional inaccuracy increase as printing speed increases. The lower print speed allows for more precise material deposition, leading to smoother surfaces and improved overall surface quality [66].

RESEARCH GAP

There is still much to learn about the long-term mechanical performance and stability of printed goods, despite the fact that a great deal of study has been done on the effects of process parameters in 3D printing. Few studies systematically examine how process inputs and their impression on mechanical and durability properties of printed items over time; despite the fact that many studies focus on optimizing process parameters to enhance print quality immediately. Understanding how various combinations of process parameters impact the mechanical properties and structural integrity of printed items in real-world settings. Examining the effects of variations in printing speed, temperature, infill density, and other process parameters could provide researchers with valuable insights on the reliability and durability of 3D-printed components.

This information is essential for process optimization and material selection.

1. Most researchers only work with five or six infill patterns; none of the researchers from the above-mentioned literature study all of the available 3D printer infill patterns.
2. No researcher concentrated on determining the printed pieces weight.
3. The printed parts' print time was not a focus of any of the researchers.
4. The majority of researchers concentrated on the quality and mechanical characteristics of printed items made of single materials like PLA, ABS, and PET-G, among others.
5. In their research, none of the researchers use Functional Graded Material (FGM).

CONCLUSION& FUTURE SCOPE

This review study concludes by emphasizing the critical role that print parameters play in 3D printing and their enormous influence on printer performance as well as the quality of the printed objects. By carefully examining layer height, infill density, print speed, temperature settings, and material selection, we have learnt a great deal about how different print parameters affect surface polish, mechanical qualities, print accuracy, strength, and overall print quality.

A crucial element in obtaining good 3D printing results is optimizing print parameters. It has been proven that cautiously modifying these parameters can enhance surface finish, structural integrity, and shorten print times. The best settings for certain applications must be determined by using a balanced approach because there is frequently a trade-off between various factors. This review emphasizes the significance of comprehending how changes to one parameter can affect other print parameters because of how intricately the print parameters interact. Users can optimize their printing procedures and get the best outcomes by using this knowledge.

Tolerance analysis and quality control are essential for maintaining the precision and dependability of 3D-printed products. Users can verify the print quality and highlight any potential problems or areas for development by using appropriate evaluation techniques. The review emphasizes the practical applications of print parameter optimization through case studies and real-world examples. These success stories teach important lessons and spur new developments in the 3D printing industry. New trends and study focuses are emerging as technology keeps developing. Future additive manufacturing will be influenced by improvements in 3D printing technology and the introduction of innovative print settings. By exploring these frontiers, new opportunities and applications in numerous industries will become available.

Sustainability features of 3D printing, pointing out areas that require more investigation, like assessing life-cycle energy consumption and other workplace risks. The research work examines the possibilities of combining 3D printing and recycling, evaluating the printability of recycled materials and contrasting their performance with that of conventional materials. It also suggests that process parameter optimization can significantly improve the sustainability of additive manufacturing. According to the research work, 3D printing with recycled materials can cut down on material waste and support more environmentally friendly production methods [71–72].

In conclusion, our in-depth analysis highlights the significance of print parameter optimization in 3D printing. Users can increase print quality, mechanical strength, and performance overall by taking into account the relationships between various factors and taking advantage of their interactions. This understanding will be necessary in realizing the full potential of this game-changing technology as 3D printing continues to revolutionize various industries and product development. To advance the state-of-the-art in 3D printing and spur innovation in a variety of industries, researchers, engineers, and practitioners are urged to build on the findings of this review.

Future Scope

With continual developments in technology, materials, and process parameters, the world of 3D printing is always changing. A review article on the impact of 3D printer process parameter might therefore cover a number of fascinating future approaches and areas of research. Future possibilities for such a review paper include the following.

Emerging 3d Printing Technologies

As new 3D printing technologies and procedures continue to emerge, it would be helpful to assess how these advancements impact the choice and optimization of process parameters. Insights into the advantages and difficulties of novel printing technologies, such as high-speed printing, continuous printing, and printing on many materials, might be gained, for instance, by examining the implications of these technologies.

Advanced Materials And Composites

The creation of brand-new composites and materials for 3D printing represents a potential area of study. The process parameters that are chosen and optimized are influenced by the various material properties, which could be examined in detail. Investigating the necessary parameter changes for novel materials like conductive filaments, biodegradable polymers, or high-temperature alloys is part of this.

Multi-Objective Optimization

As 3D printing is used more often in industrial settings, there is a growing need to simultaneously optimize a number of different factors, including print speed, material utilization, and part strength. The techniques and algorithms employed for multi-objective process parameter optimization and the associated trade-offs could be examined in a review paper.

In-Process Monitoring And Control

For the purpose of assuring consistency and quality, real-time monitoring and control of 3D printing processes are becoming increasingly important. Future studies could look at how sensor technology, data analytics, and closed-loop control systems are used to dynamically change process parameters during printing.

Sustainability and Environmental Impact

With a growing emphasis on sustainability, it would be interesting to learn how 3D printing affects resource utilization and waste generation, as well as how process parameters affect these factors. The evaluation could go over eco-friendly printing techniques and how they affect the caliber of the final output.

Hybrid Manufacturing

Hybrid manufacturing, or the combination of 3D printing and conventional production processes, is gaining popularity. Evaluation of the interactions between hybrid process factors and their effects on part properties may be a crucial future endeavor.

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