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IMPACT OF PROCESS PARAMETERS ON MECHANICAL PROPERTIES OF FDM 3D-PRINTED PARTS: A COMPREHENSIVE REVIEW

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Abstract

3D printing, being an additive process, has emerged as a sustainable technology for producing engineering components. However, due to the fundamental nature of the process, the mechanical strength of 3D-printed parts is still under investigation. This study provides an overview of the impact of process parameters on the mechanical properties of 3D-FDM printed characteristics. It covers an existing literature review of different process parameters that can be used to improve component strength by performing various destructive and nondestructive tests focusing on the polymeric material. This paper gives insights into the selection of process parameters for intended applications. The proper selection of process parameters has an overall impact on the strength of 3D-printed components. The senses are helpful for process parameter selection and producing 3D-printed parts with a better strength-to-weight ratio and other desirable properties.

Keywords : *3D Printing, FDM, Mechanical Properties, Process Parameters, Polymers*

Introduction

Additive manufacturing (AM) is a rapidly evolving technology integrated into manufacturing and daily life[1], [2]. Many people have heard of its commercialization, but it has gone by various names, including three-dimensional (3D) printing, rapid prototyping (RP), multilayer manufacturing (LM), and solid freeform fabrication (SFF)[3]. The additive manufacturing business has rapidly increased, grown, and progressed [4]. AM has now moved to the point that it is ready for industrial application. Most industries are interested in it because of its advantages over traditional manufacturing methods. The global additive manufacturing market was worth USD 13.84 billion in 2021, and it is predicted to increase at a compound annual growth rate (CAGR) of 20.8% between 2022 and 2030. In 2021, 2.2 million 3D printers were shipped globally, with unit shipments predicted to reach 21.5 million units by 2030 [5].

3D printing materials are in high demand worldwide due to their growing use in aerospace, healthcare, automotive, and consumer goods. Polymers, metals, ceramics, and composites make up the 3D printing market. Polymers will dominate the 3D printing materials market in 2021. 3D printing polymer objects have excellent mechanical properties, strength, and durability, which account for their large share. "3D printing polymers" includes "photopolymers," "polylactic acid," "acrylic styrene," "polyamide," "Polycarbonates," "polypropylene," "thermoplastic elastomers," and "other polymers." 3D printing metals include steel, titanium, nickel, aluminium, copper, and cobalt-chrome. FDM and FFF use layers of molten material to build objects Thermo plastic FDM filaments. FDM works with engineering plastics like polyamide (PA), thermoplastic polyurethane (TPU), and polyethene terephthalate (PET), as well as high-performance thermoplastics like PEEK and PEI [6].

The term "3D printing" refers to a relatively new manufacturing process that involves the layer-by-layer creation of a product based on a computer-aided design model that has been sliced [7]. The elimination of restrictions in the design and construction of complex geometries while utilizing the least amount of material possible are the two aspects of 3D printing considered the technology's most significant benefits [8]. It has many benefits, including decreased wasted material, rapid prototyping, the ability to build intricate parts without the assistance of specialized tooling, the capacity to work with multiple materials, simple customization of parts, and independent operations [9]. Despite these benefits, 3D printing techniques still offer inferior mechanical properties due to additional porosity and anisotropy caused by the nature of the manufacturing process by layers. This additional porosity and anisotropy reduce the material's overall strength [10]. In today's industrial landscape, additive manufacturing plays an essential part in producing components with reduced and intricately shaped geometries. This process results in the production of actual net shape parts and prototypes of the components or products being manufactured. In addition, this method does not require lubrication; consequently, it revolutionized the manufacturing and design industries [11].

However, despite the progress made in this area, there still needs to be more knowledgeable regarding the links between the conditions of the manufacturing process and the final mechanical performance of these components. This lack of knowledge impedes both the further development of this technology and its commercialization. The mechanical strength of 3D-printed engineering components is a topic of ongoing research.

3D Printing Technologies

In additive manufacturing, a part is printed by adding layers rather than removing materials, as in traditional machining [12]. Seven primary categories can be used to categorize additive manufacturing technologies. These categories are as follows: binder jetting, directed energy deposition, material jetting, material extrusion, powder bed fusion, sheet lamination, and vat photopolymerization [13][11][14]. FDM is used in many fields, including construction, model making, manufacturing commodities, medical, electrical, and engineering fields, and more. The fused deposition modeling (FDM) technique was developed as a part of the technology used for 3D printing in the 1980s [15]. Among the many 3D printing methods used to create plastic components, Fused Deposition Modeling (FDM) is a popular choice [16]. FDM involves feeding a thermoplastic filament into the 3D printer; the filament is heated to its melting point through a heated nozzle and then extruded onto the build platform, tracing the part dimensions specified by the STL file. As the first complete layer is finished, the print head moves up by one-layer height before tracing the next layer. This continues, layer by layer until the part is complete Fig. 1

shows the steps involved in the FDM, from CAD model generation to part cleaning [17].

Figure.1 Steps involved in FDM

Fused Deposition Modeling is a material extrusion-based process that involves heating polymer filaments to the desired temperature. The melting temperature is set, and the nozzle head is moved layer by layer in the correct direction to create the part. The nozzle moves by the codes generated by a 3D model of the object to be printed. It is distinguished by various materials, ease of accessibility, durability, low cost, and a wide range of usability [18].

AM materials are generally classified as Amorphous, Semi-Crystalline [19]. Depending upon the process, plastics are categorized as amorphous polymers or semi-crystalline polymers. ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene Terephthalate Glycol), PLA (Polylactic Acid), TPU (Thermoplastic Polyurethane), and POLYCARBONATE are some thermoplastic materials used in fused deposition modeling [20][14][8][21]. Fig. 2 summarizes the availability of essential thermoplastic polymer types as filaments. These materials are characterized by several features, including resistance to ultraviolet radiation, hardness, transparency, and biocompatibility. A continuous filament with thermoplastic composition is required to carry out this commonly employed AM method [19]. industry, automotive industry, tooling applications, and so on [17][23][24]

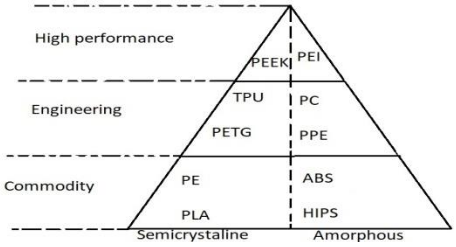

Figure: 2 Material used in FDM[22]

AM materials are generally classified as Amorphous, The characteristics and uses of several material types are listed in Table 1. FDM has applications in the medical industry, aerospace industry, automotive , tooling.

Table 1. Materials, properties, and applications in FDM method

Material class	Material	Properties	Applications
Thermoplastic Polymer	**ABS**	High strength , temperature resistance[25]	Light weight construction [1]
	PLA	higher dimensional accuracy, Biodegradable, brittleness, low strength, [26]	Biomedical application Good material for prototype ,medical and pharmaceutical[27]
	PETG	High strength, Impact resistance, resistance to high temperature , UV rays , water and chemical solvent [17]	Medical devices, suitable for aerospace and aerodynamics application[17]
	TPU	Flexible, excellent tensile strength [8]	Automotive application [8]

Process Parameters:

This study aims to demonstrate that the appropriate selection of process parameters is essential for the printing of parts and that an investigation into the various available material properties is essential since the component's strength is affected by these attributes. Additionally, it has an impact on the part's quality as well as its dimensional stability. Fig. 3 shows process parameters in FDM. The printing process known as FDM depends on several parameters that have been briefly mentioned. For simplicity, these can be divided into three macro categories:

1.Relying on geometry (Nozzle size, filament size)

2.Based on a process (Melting tempt, Bed Heat, Printing Speed)

3.Parameters based on the structure (Layer thickness, Infill geometry, Infill density, Number of layers, Raster angle, Raster gap, and Raster width).

The additive manufacturing technique is employed extensively in many aspects of our daily life. It is becoming an increasingly important part of how we go about our daily lives. It has been tremendously successful in various sectors, including medical science and aerospace. The quality of the products has been our primary focus. The cause and effect diagrams of the various process parameters for the various attributes are depicted in Fig. 4.

In order to print, the material of the highest possible quality is required to research all of the process parameters involved in the printing process. The literature review details several significant mechanical properties and how those qualities vary throughout the operation.

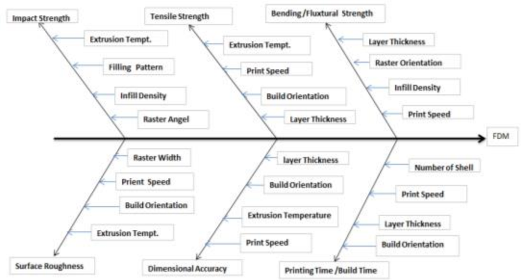

Figure.4 Fish-bone diagram of process parameters and properties

The material deposition pattern used to create the internal structure of the FDM printed part [30]. The raster angle is measured along the X-axis of the build platform where extruded material is deposited [31].

Figure.3 Process parameters in FDM

Some critical process parameters are defined as Layer thickness, the thickness of the deposited layer on the print bed [28]. In FDM, the temperature of extrusion is the temperature at which the filament of thermoplastic materials is heated in the nozzle before extrusion. The infill density indicates the percentage of material required to build a product [29]. The infill pattern is

Process Parameters And Mechanical Properties

Deepak et al.[9] PLA and composites were investigated for mechanical properties and fracture morphologies. Printing parameters such as layer height (0.10 mm, 0.15 mm), print angle (0, 90), and print speed (50 mm/s, 80 mm/s) were varied in the current study to create arrays of experimental trials to estimate the tensile UT-04-0100 capacity of 100 kN, and flexural 3-point bend, the distance between supports was 60 mm. Furthermore, using field emission scanning electron microscopy, the researchers highlighted fracture morphologies and classified the types of fractures in PLA neat and composite samples. An analytical model was used to validate the results of micrographs for estimating tensile and bending strengths. The results showed that the percentage increase in Young's modulus was greatest for composites reinforced with carbon fiber and brass. In the flexural test, composite samples outperformed tensile samples.

Abdul et al. [31] Explores the impact of raster angle α= 0, 45, and 90◦ concerning the fluidic oscillator performance parameters.

Effects of FDM raster angle on fluidic oscillator flow and energy characteristics are studied experimentally. For an extensive range of inlet mass flow rates m = 2-9 g/s, the performance is evaluated based on the jet's external properties and the actuator's overall energy efficiency. Three different 3D printers' output is compared to a smooth machined sample at raster angles of 0, 45, and 90 degrees. Surface finishes produced by printing at varying raster angles were notably different, significantly affecting the actuator's overall performance. The results show that the optimum raster angle for all three tested printers is 0 degrees, with a raster angle of = 45 degrees to be avoided. The striking result is that the oscillator's performance with an indistinct raster direction pattern is significantly improved, especially for = 90, despite higher surface roughness.

Liu et al. [29] Performs experimental and numerical investigations to develop empirical equations for estimating the output force, the output displacement, and the input force corresponding to given values of the input displacement and infill density of the compliant finger, which is 3D printed with (TPE) filament. Four flexible finger prototypes are made with 40%, 60%, 80%, and 100% infill. The correlation between infill density and maximum payload is also studied, creating a two-fingered gripper. Testing revealed that grippers with higher infill density could lift a heavier payload. Maximum payload as a function of infill density was found to be best described by a polynomial of degree four. When both fingers had a 100% infill density, the gripper could hold 7.81 kg.

Tang et al. [32] They studied the effect of process parameters on the mechanical properties of the samples by analyzing digital image correlation images of 3D-printed PLA lattice structures. FDM prepared tensile samples as well as PLA lattice structures. The samples were subjected to tensile tests to determine their tensile strength and elastic modulus. In addition, the yield strength, plastic platform stress, and densification strain were obtained through compressive experiments performed on the 3D-printed PLA lattice structures. At the planned process parameters of printing temperature (200, 210, 220, 230, 240 (°C)) and printing speed (30, 40, 50, 60 mm/min), the mechanism of the influence of process parameters on the sample was analyzed. The experimental data demonstrate that the tensile strength and elastic modulus increase and decrease as the printing temperature is raised. Increases in tensile strength of 4.3% and elastic modulus of 11.06 % are seen when printing temperatures are raised from 200 to 230 degrees Celsius. The tensile strength and elastic modulus drop by 1.02% and 3.32%, respectively, when the printing temperature is raised from 230 °C to 240 °C. The maximum tensile strength is 50.16 MPa, and the maximum elastic modulus is 4340.38 MPa.

Chang et al. [33] They used ultrasonic fatigue testing to analyze the fatigue resistance of 3D-printed CFRP. Carbon fiber-reinforced plastic 3D printed parts have excellent properties, but there needs to be more research on their durability, which limits their practical application. An experiment was conducted on three specimens mixed in the bidirectional and unidirectional of 0 and 90. The resonance at 20 kHz was confirmed by numerical analysis. Ultrasonic fatigue testing was used to examine the designed specimen from low to high cycles thoroughly, and differences in a lifetime were confirmed through comparison. FEM was also used to model the fatigue failure phenomenon based on the specimen's life analysis results.

Shanmugam et al. [20] They Reviewed the literature on the effect of process parameters on the mechanical strength of FDM-printed polymeric materials, focusing on fatigue behaviour under cyclic loading conditions for biomedical applications. The versatility of 3D printing technology has enticed several industries to print complex geometrical structures, emphasizing the importance of studying the mechanical strength of FDM printed parts. FDM-printed materials outperform conventionally manufactured polymeric materials (e.g., injection moulding). Experiments on PLA and ABS-based printed materials show that an orientation of the raster angle of +45°/-45° yields a longer fatigue life. The process parameters are raster angle (0, 45, 90, -45), infill density (10, 20, 30), and infill pattern (rectilinear, honeycomb, triangular, wiggle). Polymeric materials are viscoelastic, and typical FDM and fatigue processes involve temperature changes. Polymers have a shorter fatigue life in hotter environments.

Mohammad et al. [34] They aimed to create 3D-printed polymer plates with an open holes and improve their mechanical strength and structural integrity. The mechanical strength of 3D-printed plates with open holes subjected to tensile loads during the operation was investigated experimentally. Various factors, including hole diameter and specimen width, affect the tensile strength of components made from FDM-processed Polylactic Acid material. Strength and the impact of the specimen width-to-hole diameter ratio on structural integrity were determined through a battery of static loading tensile tests. Parallel to the experimental tests, numerical simulations are run, and there is good agreement between the experimental and simulation results. Experimental results and numerical analysis show that specimens with a small hole (w/D=6) have a higher tensile strength. A smaller hole diameter results in greater average strength.

Ibrahim et al. [35] Concluded fiber-reinforced composites are replacing metals and thermosetting polymers because of their lightweight structure and superior mechanical performance. Hence, researchers at the University of Delaware studied samples of Nylforce CF/GF composite materials manufactured at three different raster orientations (0, 45, and 90). Flexural tests were performed at three points. At room temperature, the nylon + GF composite had the highest stiffness (modulus), indicating that it can withstand bending forces better. Nylon + CF composites exhibited elastic behavior, lower flexural strength, and higher deflection.

Josef et al. [36] They investigated the effect of raster layup on FDM 3D-printed PLA material's material properties. Examine the resulting toughness, strength, and stiffness, focusing on toughness. The results of typical layups with 90° between-layer orientations show that stiffness and strength are nearly isotropic, while toughness displays strong anisotropy. When loaded diagonally to the raster, the material has much higher toughness than when loaded parallel or perpendicular.

Popa et al.[37] Performed the Izod impact test on PLA and PETG samples that had a notch embedded on one side, were fixed so that the notch was at the bottom of the embedment, and had the notch facing up. With raster angles of 45° for the infill, a density of 100% was defined. The printing layer thickness was 0.15 mm. Each material was given four thicknesses: 4, 6, 8, and 10 mm. The specimens were tested using the CEAST 9050 pendulum impact system following ISO 180:2000. The IZOD impact strength values for both materials are similar. However, while the PETG specimens allow for more deflection, the PLA specimen has a higher impact force. The PETG specimens produced more accurate results.

Jelena et al. [38] They investigated the effect of polylactic acid, Polycarbonate, and polyethene terephthalate glycol on the mechanical properties of parts. Samples are designed following ASTM standards and manufactured using the same process parameters. Different materials provide different mechanical properties for the part. The mean effect on tensile and flexural strength has been investigated. Tensile and 3-point bending tests were carried out. The study concludes that there is a difference in the results, as expected. No material excels in every way; different materials serve different purposes.

Hanon et al. [39] They measured the effect of 3D printing parameters on the hardness and tensile strength of PLA polymer. Layer heights of 0.1 mm, 0.2 mm, and 0.3 mm, as well as a range of raster direction angles (0/45, 45/135, and 45/90), are considered. Images captured with an optical microscope helped researchers determine the nature of the 3D prints' surfaces and their overall quality during the experiments. Also specified were the fracture patterns. A correlation between hardness and tensile strength was evaluated based on the performance attained from the investigated print parameters to fill the knowledge gap concerning the behavior of 3D-printed materials. The obtained results demonstrate that mechanical characteristics were significantly reduced at a [0/45°] raster angle but that the raster direction angle settings did not have a dominant influence on hardness. Shore D hardness and mechanical properties such as UTS and elongation at UTS and elongation at break are affected by a layer thickness of 0.1 mm. In comparison, a layer thickness of 0.2 mm increases Young's modulus. Compared to the other investigated 3D printing process factors, the print orientation has the highest contribution parameter that affects the mechanical properties of the used PLA material.

Rishi et al. [40] They studied the effects of three popular filaments on the environment throughout their lifecycles, from raw material extraction to finished product disposal. Endpoint and midpoint environmental impacts and hotspots have been estimated. The research helps stakeholders compare the environmental impacts of various materials and choose the most environmentally friendly material. Climate change, fossil fuel exhaustion, freshwater Eco toxicity, human toxicity, ozone depletion, particle matter formulation, terrestrial acidification, and water depletion are all examples of impact categories. PETG material is the most environmentally friendly across all mid-point and endpoint parameters, whereas ABS material is the least environmentally friendly. Despite being derived from natural resources and biodegradable, PLA material has the most significant negative impact on water depletion and freshwater Eco toxicity. The recycling phase has been found to have the most significant environmental impact throughout the product's life cycle.

Feiyang et al. [25] They investigated the effect of 3D printing parameters on the crack growth of ABS components. In order to produce the high with varying printing parameters, including building orientations (0°, ±45° and 90°), nozzle size (0.4, 0.6 and 0.8 mm) and layer thickness (0.05, 0.1 and 0.15 mm), experimental results showed that the specimen with 0° building orientation, 0.8 mm filament width and 0.15 mm layer thickness vibrated for the longest time before the fracture at every different temperature.

Muammel et al. [41] They examined initially to determine how the presence of color influences the tribological properties of 3D-printed PLA polymer. The print orientation and color impact are evaluated by producing samples in different directions (horizontal, 45-degree angle, and vertical) and filament colors (white, black, and grey). At the same time, tribological tests are performed in reciprocating sliding at two different applied loads (150 and 200 N). Multiple images are captured using surface roughness, product hardness, and microscopy. Results show that tribological behavior varies depending on the print orientation and filament color. The maximum friction tendency is associated with white filament color, while the maximum wear depth is associated with test pieces with a 45-degree orientation and black filament color. The stick-slip phenomenon is more likely to occur at low loads, but sliding under high loads helps to reduce wear.

Nectarios et al. [42] They investigated the effects of six 3D printing control parameters on the quality mentioned above indicators: raster deposition angle (0, 22.5, 45, 67.5, 90), infill density (80, 85, 90, 95, 100), nozzle temperature (195, 200, 205, 210, 215), bed temperature (40, 45, 50, 55, 60), printing speed (30, 40, 50, 60, 70), and layer thickness (0.10, 0.15, 0.20, 0.25, 0.30). The robust design theory was used to process the experimental data. An L25 Taguchi orthogonal array (25 runs) with five levels was constructed for each control parameter. Determine how they affect three critical quality indicators (CQI) for MEX 3D printing with PLA material (surface roughness, dimensional accuracy, and porosity) and quantify that effect. MEP diagrams and Taguchi analysis were used to identify the control factors influencing rank. Interaction plots showed that no single set of control parameter values maximized all three CQI.

Anis et al. [27] They were designed to test a set of optimized parameters such as nozzle temperature (180, 210, 240 0C), print speed (40, 80, 120), infill density (50, 75, 100), and infill pattern (grid, triangular, trihexagonal) to produce cost-effective, lightweight parts with enhanced impact strength and hardness properties. A fused deposition modeling (FDM) 3D printer fabricated Izod test specimens according to the ASTM D256 standard. The experimental runs used an L9 array of Taguchi design experiments, and the impact tester and digital Shore durometer were used to evaluate the performance of the fabricated specimens. The Izod impact strength was highly influenced by print speed and infill density. With the highest nozzle temperature, the middle print speed, and the medium infill density, the grid-type infill pattern showed the highest impact strength (113.84 J/m). Due to the presence of fiber, the maximum hardness observed at 79.6 (Shore D) is 37.95% higher than pure PLA.

Krishna et al.[43] Conducted experiments to determine the effect of six important print parameters on the dimensional accuracy of ABS specimens printed using these settings: wall thickness (0.8, 1.20, 1.6), infill density (20, 35, 50), build plate temperature (80, 95, 110), print speed (30, 47.5, 65), layer thickness (0.1, 0.20, 0.30), and extrusion temperature (225, 232.5, 240). The experiments were run, analyzed, and an ANOVA was created using a small-resolution central composite design (CCD). This study found that the dimensional accuracy of 3D-printed parts is most affected by layer thickness and print speed.

Marton et al.[44] Investigated how different FDM infill patterns affected the mechanical properties of PLA test specimens in an informal bending test. Bending tests were conducted on FDM samples with various infill patterns and percentages (25, 50, 75, and 100). The infill patterns tested were a grid, honeycomb, and gyroid. The honeycomb and gyroid patterns are more mechanically resistant than the simple grid pattern.

Szust et al. [45] In a new study, they studied the effects of printing orientation, layer height, thermal annealing, and salt remelting on the tensile properties of PLA and PETG samples. After the salt remelting process, the tensile strength of PETG FDM parts measured in the Z direction increases by more than 300%, and the anisotropy of the parts becomes negligible.

Muammel et al. [46] Tested how changing 3D printing process settings affected the precision of PLA samples. Build orientation (flat, on edge, upright), raster direction angle (45 degrees, 135 degrees, and 90 degrees), and layer thickness (100,200,300 m) are just some of the process parameters used to create cylindrical and dog-bone tensile test samples. We print the necessary samples using white, grey, and black PLA filaments. Overall dimensional accuracy of 98.81% was achieved, proving the feasibility of commercial FDM 3D printers as a cheap and high-quality option for manufacturing functional components. There was an apparent variation in weight between the heaviest (white) and lightest (black) test pieces, almost 7.24%, which could be attributed to the filament's color. The layer thickness parameter had a significant impact on accuracy, whereas the raster direction angle parameter had no effect when the number of layers and contour size were both the same.

Liu et al. [16] They investigated the mechanical properties, including tensile and flexural properties, of samples made by FDM with various additives, such as wood, ceramic, copper, aluminium, and carbon fiber based on polylactic acid. Various PLA composites, build orientations (flat, on edge, upright), and raster angles (0, +45°/45°, 90°) are compared and analyzed for their effects on mechanical responses. Ceramic, copper and aluminium-based PLA composite parts have similar or improved mechanical properties to virgin PLA-made parts. In most cases, PLA composite samples printed in on-edge orientation with +45/45 raster angles have the highest mechanical strength and modulus. The fracture surfaces of the samples after tensile and flexural tests have been thoroughly examined. Wood and carbon fiber-based PLA composite parts have weaker mechanical properties than virgin PLA and PLA composites made from ceramic, copper, and aluminium because of defects like high porosity, poor compaction, and adhesion between filament layers.

John et al. [2] Aim was to create, validate, and understand their impact on mechanical properties. Taguchi experimentation and Grey relational analysis were used to determine the optimal values for the following process parameters: cell geometry (hexagonal, triangular, square, diamond, diamond angle, square angle), nozzle diameter (0.8 0.6 0.4), and strain rate (1.2, 2.5). According to the results of tensile tests conducted on six different sample patterns by the ASTM D638 standard, square-patterned samples fare the best under tension and retain the most mechanical strength. According to the grey relational analysis results, the highest grey relational grade (GRG) was attained for the larger nozzle diameter of 0.8 mm, the strain rate of 5 mm per minute, and the square cellular geometry. According to the analysis of variance, the highest contributing factor was nozzle diameter (48.99%), while cellular geometry was ranked second (40.78%).

Long et al. [47] They optimized the process parameters for the quickest print time, minimizing ultimate strength loss. While considering several process parameters, this research looks into additively manufactured PLA's mechanical properties and print time. The design of experiments (DOE) method was used with a split-plot design with five factors. ANOVA was used to validate the model's significance. The process parameters are nozzle diameter (0.4, 0.6), number of outer shells (2, 4), extrusion temperature (215, 230), infill percentage (10, 40), and infill pattern (cubic, gyroid). Increasing the number of outer shells significantly improves the test specimen's ultimate strength. In general, the ultimate strength increases with increasing numbers of outer shells, but the infill percentage has less of an effect at lower numbers of shells. Furthermore, the 0.6 mm nozzle and gyroid infill pattern improve ultimate strength at all infill percentages and shell counts. The most critical factor in increasing print time was the nozzle diameter.

Atakok et al. [48] Used Taguchi analysis to examine how different FDM production parameters affected the tensile, three-point bending, and impact strength of PLA and Re-PLA test pieces produced using additive manufacturing. Experiments were planned to determine the optimal values for the FDM process parameters of filaments (PLA, Re-PLA), layer thicknesses (0.15-0.25-0.25 mm), occupancy rates (30%, 50%, and 70%), and filling structure (rectilinear). Layer thickness, rather than occupancy rate or filament materials, was the most influential factor in increasing tensile strength, three-point bending strength, and impact strength. Layer thickness (0.25 mm), occupancy rate (70%), and filament material

(PLA) yielded the best results. Tensile strength was determined to be 60.006 MPa, three-point bending strength to be 125.423 MPa, and Izod impact strength to be 16.961 kJ/m^2.

Popa et al. [49] They investigated A numerical and experimental study of FDM-printed PLA specimens subjected to IZOD impact tests. The specimens were tested using the CEAST 9050 pendulum impact system following ISO 180:2000. The experimental measurements have been numerically modelled using the LS-DYNA explicit module of the ANSYS finite element software. A strong correlation was found between the numerical model and the experimental tests. Based on the results of the numerical analyses and the experimental determinations of the impact parameters, it was found that additively manufactured materials can be modeled numerically and calibrated with experimental ones, which is a boon for using numerical models in the automotive, aerospace, and medical industries. The calculated kinetic energies match the measured data. The numerical analysis of PLA material reveals that the kinetic energies of 6 mm thick specimens are 0.03 J, 8 mm thick specimens are 0.047 J, and 10 mm thick specimens are 0.068 J. Results from experiments show that the average energy is 0.0186 J for the 6 mm thickness, 0.0544 J for the 8 mm thickness, and 0.0858 J for the 10 mm thickness.

Aboma et al.[50] They investigated the effect of process parameters on the tensile properties of FDM components. The investigation is conducted on the high-performance ULTEM 9085 polymeric material, and five parameters are taken into account: air gap (-0.0254, 0.0000), raster width (0.4064, 0.7814), raster angle (0, 90), contour number (1, 5) and contour width (0.4064, 0.7814). According to the investigation results, only one of the considered parameters (the raster angle) had a significant influence on the material's tensile properties.

Marșavina et al.[51] Examined how manufacturing parameters affected the tensile and fracture properties of PLA elements produced using FDM. The outcomes of changing the growth orientation (horizontal vs vertical), building orientation (0 degrees, 45 degrees, and 90 degrees), printer type (Prusa i3 MK3 vs WN400 3D Platform), layer thickness (0.15 and 0.40 mm), specimen thickness (4 and 10 mm), and filament color (black, white, and grey) (purple, white, black, grey, red, and orange) It has been found that the tensile and fracture properties of FDM 3D-printed PLA specimens depend on the manufacturing parameters studied. The fracture mechanisms and crack propagation are a step-by-step process, according to the microstructural analyses of the SENB fracture surfaces. In the end, charts of material properties (Young's modulus and mode I fracture toughness versus tensile strength) are drawn up.

D'Addona et al.[52] They investigated a method based on desirability functions for optimizing FDM process parameters. Several process parameters control FDM's performance and can significantly alter the price and quality of the 3D-printed components. Three important FDM process parameters are chosen for optimization: layer thickness (0.15, 0.20, and 25), infill percentage (55, 65, 75, and 85), and speed (70, 80, 90, and 100). Based on the findings, the following conclusions can be drawn: The Desirability Function Approach is a powerful tool to optimize process parameters for multi-response manufacturing processes. The best parameters for the FDM process are layer thickness of 0.3 mm, speed of 81.5152 mm/sec, and infill percentage of 55%. The predicted results for the optimal parameters are as follows: filament length consumed 2.12 m, component weight 5.69 g, and printing time 20.65 min. Actual responses for these optimum parameters are as follows: filament length consumed 2.10 m, component weight = 5.68 g, printing time 20.01 min.

Muhammad et al.[53] Analyzed the impact of oxygen concentration in the 3D printer chamber on mechanical properties, including tensile strength and surface roughness, and looked into the connection between layer thickness and surface roughness. Samples printed with 0.1 mm, 0.2 mm, and 0.3 mm layers of an Acrylonitrile Butadiene Styrene (ABS) resin were subjected to tensile and surface roughness tests in an FFF 3D printer (ABS). According to this research, controlling the oxygen level in the 3D printing chamber improved the tensile strength of the 3D printed part. However, increasing the oxygen concentrations from 10% to 20% has no discernible effect. Furthermore, surface roughness improved with lower oxygen content or no oxygen in the chamber. In other words, removing oxygen from the 3D-printed chambers improved tensile strength and surface roughness.

Laxmi et al.[54] They developed a chunk-based printing approach to investigate the mechanical strength of chunk-based printed parts for cooperative 3D printing. The workpiece is divided into small chunks before being assigned to an army of robots for chunk-based printing. The bond strength at the chunk joint is a mystery, although chunk-based printing has been shown to speed up printing and scale up a print size. Parameters associated with chunk-based printing, such as the chunk slope angle and overlapping depth, can directly impact bond strength. The experiment is designed using various combinations of these parameters. Based on the experimental results, we conclude that chunk joints do not reduce the strength of chunk-based printed parts when the chunk-based printing parameters are chosen correctly. As a result, the findings validate chunk-based printing and provide the foundational knowledge for future chunk-based cooperative 3D printing.

Kovan el al.[55] They investigated how changes in layer thickness and printing temperature affected the surface qualities of the final PLA samples. Printing parameters significantly affected surface roughness across all three printing temperatures (190 C, 210 C, and 230 C) and all three layer thicknesses (0.1 mm, 0.2 mm, and 0.4 mm). If the printing temperature is held constant and the layers are laid down vertically, surface roughness values tend to increase with layer thickness. Printing at lower temperatures rather than higher ones results in better surface quality.

Mohammad et al.[56] Examined and researched how 3D-printed polymer components crack. Samples were printed in three raster directions (0, 45, and 90) to see how they affected the fracture behavior of the components. Another set of test coupons was printed using wood-reinforced PLA material. Tensile tests were performed on all specimens and investigated the fracture behaviours. Finite element analyses using the anisotropic phase-field fracture model were also performed in parallel with the experiments. The structural integrity of the specimens is determined based on experimental tests for fracture load and stiffness. Results show that unaltered 0 PLA is the most robust material, while defected 90 PLA-wood samples are the least sturdy.

Raja et al.[57] Using the FDM manufacturing process, used the tensile test to determine the optimal printing parameters for Polylactic acid filament. All of the print settings that can be adjusted on FDM machines are considered to achieve the best results. This includes the extruder temperature, bed temperature, layer height, printing speed, travel speed, infill, and shell count. Additionally, tensile specimens from the ASTM (American Society for Testing and Materials) D638 standard were produced using PLA filament with the aforementioned tweaked printing parameters. The best printing parameters for PLA products were determined by the time recorded during production and the tensile test results after production. As a result of these studies, one can determine the optimal settings for printing with PLA filament.

Martina et al.[58] Studied Masked stereo lithography structural part' thermo-mechanical properties depend on processing parameters and post-processing (MSLA). Post-treatment implementation often yields poor printouts. A commercial free-radical photopolymerization (FRP) resin was used to develop and demonstrate a novel tool for complex 3D-printed body characterization. Heat deflection temperature (HDT) and dynamic mechanical analysis (DMA) can be used together to quickly and accurately characterize photopolymer curing parameters. Network density was examined after post-curing time. 3D-printed cellular bodies and residual stress mitigation are also discussed. Print orientation affects mechanical properties. Print orientation significantly affects HDT and break temperature. The x-direction printing was the most mechanically resistant because the applied force was perpendicular to the printed layers and weak interlayer regions. The combined DMA-HDT analysis showed that mechanical properties changed depending on the orientation of the printing layers about the applied force and stress transfer within the material, but thermal properties did not.

Rouf et al.[5] Discuss the various ways in which 3D printing is used to manufacture industrial products, the various process parameters involved in each process, and how they affect the mechanical properties of these parts, such as fatigue, tensile, and bending strength, among others, with a focus on polymeric materials. Researchers have looked into mechanical strength because of the way the process works. The mechanical integrity of 3D-printed components is a topic of study. An optimized set of parameters can result in a 3D-printed part with a higher strength-to-weight ratio and other desirable properties depending on the intended use. Based on waste reduction, reduced labor costs, and other advantages

Irene et al. [59] Present paper to evaluate the dimensional accuracy and forms errors of FFF (fused filament fabrication) 3D printed spur gears made from

PLA and Nylon-PA6 polymeric materials. Two different gears were designed and printed, each with its module and number of teeth. First, the gear modeling process is described. Both materials' printing parameters were set. The methods of measurement were then explained. The sector span technique calculated the gears' base circular thickness and pitch. Diameters were measured from base to tip, and deviations in roundness and concentricity were calculated. The findings indicate that PLA generally permits higher dimensional accuracy than nylon. Lower infill ratios yielded more accurate nylon parts than PLA ones.

Soleyman et al.[7] Work on novel shape memory polymer (SMP) Poly-Ethylene Terephthalate Glycol (PETG) thermo-plastic structures, with highly controllable self-coiling and tensile shape memory behaviors, are introduced through 3D printing. The tensile shape memory test was done on a dog-bone tensile sample printed with a cross pattern to evaluate the effect of the first layer's printing direction, programming temperature, and strain rate on the tensile shape memory performance. The results showed that the maximum printing-induced pre-strain of the PETG is stored in the first printed layer. Manipulating the infill printing direction of the 3D-printed PETG strip provides different controllable shape transformation modes, including bending and spiraling. The wall effect experiments indicated that the shape.

From the literature review, some crucial factors are tabulated in Table 2, such as Materials, testing Standards, Process parameters and Mechanical Properties in FDM.

Table 2. Materials, Testing standards, Process parameters and properties in FDM

Material	Testing Specimen, Standard	Process parameters	Mechanical Properties
PLA	ASTM D638 ASTM F2921, D2240, D618, D5766	Infill density , Infill pattern, Infill percentage, layer thickness, Air Gap, printing speed, nozzle diameter, nozzle temperature, Build orientation, filament colors	Tensile strength[54] [34] [57] [2] [47] [56], Fracture behavior[16] **,** Surface properties[55] & dimensional accuracy[42] [59], flexural 3-point bend[9], product hardness[41] [46] [27]
PLA	ISO178:2011,ISO 527,ISO180:2000, ISO 527–1, ISO 527-2	Infill density, Infill patterns, infill percentage, Layer thicknesses, Build orientation, layer thickness, and filament color.	Bending strength[44], Impact strength[48] [49] [36], tensile strength[51] [32], hardness[39]
PETG	ISO 180, ISO 527-1:2019, ISO 14040 , ISO 527–2:2012	Infill density, Raster angle, layer thickness, Printing speed and printing temperature, Nozzle diameter	Izod impact[37] , Tensile strength[7] , flexural strength[38], Life cycle assessment[40]
ABS	ASTM D638, ISO 12108	Infill density , Layer thicknesses Build orientations, Nozzle size, print speed.	Tensile and surface roughness[53],Dimensional accuracy[43]

Conclusion

The reviewed literature summarized that additive manufacturing is a developing technology at an infant stage with the potential to challenge conventional manufacturing processes. The following grey areas are identified to enhance 3D printing capabilities:

- FDM is the most commonly adapted technology. FDM is suitable for polymeric materials.
- Many researchers have attempted to determine the complexity of the FDM technique by examining the various input process parameters under ASTM standard testing circumstances.

- The process settings significantly impact the mechanical, thermal, and tribological properties of 3D-printed objects.
- Print orientation and filament color affect tribological performance. White filament friction is the highest black filaments wear the most.
- Top surface roughness varied with layer thickness. Surface quality decreased with layer thickness.
- Depending on the intended use, a 3D-printed component with an enhanced strength-to-weight ratio and other desirable characteristics may be produced using an optimum set of parameters.
- Ultimate tensile strength values varied with test speed, as shown by detailed comparisons. When layer thickness increased, this was more apparent.
- Due to their high fill rate and weight, excellent pipe models have the highest compression strength and elasticity modulus.
- There is scope for multi-objective optimization with different input parameters.
- Assessment of essential parameters determining the quality of 3D printed parts and a study into the performance of FDM printed specimens utilizing various tests including tensile, compressive, and bending.
- Future research could focus on engineering uses of polymer base materials like PETG, TPU, and POLYCARBONATE, with or without adding reinforcement of fiber, to increase the strength of 3D-printed parts and make the processes more effective and compatible with a wide range of materials, in addition to Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).

The reviewed literature confirms that additive manufacturing is a developing technology with the potential to challenge traditional manufacturing methods.

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