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A Review on the Impact of Polylactic Acid (PLA) Material on Products Manufactured Using Fused Deposition Modeling (FDM) Additive Manufacturing Method

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ABSTRACT

This compilation article extensively examines the role and impact of Polylactic Acid (PLA) material in products manufactured using Fused Deposition Modeling (FDM) method in additive manufacturing (AM). Presently, 3D printing technologies are rapidly proliferating across numerous industries and applications. Performance and impact in the FDM printing process can vary based on factors like; infill pattern, printing orientation, PLA's melting temperature, feed rate, and layer thickness. Infill patterns and printing orientation significantly affect the mechanical durability, surface quality, and printing duration of the product. Hence, the identification and optimization of suitable parameters are crucial for the effective utilization of PLA in 3D printing. This compilation gathers research from the existing literature regarding PLA's role and performance in the FDM printing process, encompassing PLA's structural and mechanical attributes, the influence of printing parameters and infill patterns, and the industrial applications of products manufactured using PLA. Specifically, the physical and chemical characteristics of PLA, optimization of printing parameters, geometry of infill patterns, printing orientation, and layer structure are examined. This study aims to provide a comprehensive reference regarding the characteristics and performance of PLA. It is intended to be a valuable resource for researchers, industry professionals, and academics engaged in the fields of design and engineering.

Eriyik Yığdırmalı Modelleme (FDM) İmalat Yöntemi Kullanılarak Üretilen Ürünler Üzerinde Polilaktik Asit (PLA) Malzemenin Etkisine Dair Bir İnceleme

ÖZ

Bu derleme, Eklemeli İmalat (AM) yöntemlerinden olan Eriyik Yığdırmalı Modelleme (FDM) yöntemi kullanılarak üretilen ürünlerde Polilaktik Asit (PLA) malzemenin rolünü ve etkisini geniş bir şekilde incelemektedir. Şu anda, 3D baskı teknolojileri pek çok endüstri ve uygulama alanında hızla yayılmaktadır. FDM baskı sürecindeki performans ve etki; dolgu deseni, baskı yönü, PLA'nın erime sıcaklığı, besleme hızı ve katman kalınlığı gibi faktörlere bağlı olarak değişebilir. Dolgu desenleri ve baskı yönü, ürünün mekanik dayanıklılığını, yüzey kalitesini ve baskı süresini önemli ölçüde etkiler. Bu nedenle, PLA'nın 3D baskıda etkili kullanımı için uygun parametrelerin belirlenmesi ve optimizasyonu hayati önem taşır. Bu derleme, PLA'nın FDM baskı sürecindeki rolü ve performansı hakkında mevcut literatürden araştırmalar toplar ve PLA'nın yapısal ve mekanik özelliklerini, baskı parametreleri ve dolgu desenlerinin etkisini ve PLA kullanılarak üretilen ürünlerin endüstriyel uygulamalarını kapsar. Özellikle, PLA'nın fiziksel ve kimyasal özellikleri, baskı parametrelerinin optimizasyonu, dolgu desenlerinin geometrisi, baskı yönü ve katman yapısı incelenmektedir. Bu çalışma, PLA'nın özellikleri ve performansı hakkında kapsamlı bir referans sağlamayı amaçlamaktadır. Tasarım ve mühendislik alanlarında çalışan araştırmacılar, endüstri profesyonelleri ve akademisyenler için değerli bir kaynak olmayı hedeflemektedir

Anahtar Kelimeler: Eklemeli İmalat, Eriyik Yığdırmalı Modelleme, Polylactic Acid, Dayanım testi, Polimer

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1. Introduction

Additive Manufacturing (AM) technologies have brought about a profound transformation in the manufacturing industry by enabling the production of intricate parts, offering opportunities for rapid prototyping, and facilitating functional manufacturing. In contrast to traditional manufacturing methods that involve subtractive processes like cutting or machining, additive manu facturing constructs three dimensional components layer by layer, providing unparalleled design flexibility and customization prospects. This capability has led to remarkable advancements in various sectors, including defense, aerospace, automotive, dentistry, and biomedicine [1, 2].

Fused Deposition Modeling (FDM) stands out as a widely adopted additive manufacturing technique, recognized for its versatility, cost effectiveness, and availability in desktop 3D printers [3]. FDM involves the gradual fusion of thermoplastic filaments, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), to fabricate three dimensional objects. This technology has evolved from applications in rapid prototyping and visual aids to func tional part production in industries like aerospace and biomedicine [4-6]. Nonetheless, the widespread adoption of FDM for functional part manufacturing has been hampered by certain limitations. Achieving optimal quality and mechanical properties in parts produced with FDM necessitates meticulous evaluation of various printing parameters, including configuration method, layer thickness, infill patterns, and feed rate. These parameters exert significant influence on the structural and mechanical performance of parts created through FDM [7, 8].

Among the array of materials suitable for FDM, PLA has emerged as a favored choice. PLA is an aliphatic polyester derived from renewable sources, such as starch, offering a more sustainable alternative in contrast to fossil based polymers. PLA's low melting temperature facilitates seamless processing in desktop 3D printers, rendering it a preferred option for hobbyists and small scale production endeavors [9]. Despite PLA's popularity, a comprehensive comprehension of its performance within the FDM process remains incomplete. While previous research has delved into the effects of various process parameters on FDM parts, there exists limited literature specifically addressing the mechanical properties of PLA based products manufactured using low cost 3D printers. Additionally, further research is imperative to explore the influence of printing orientation, layer thickness, and feed rate on the mechanical performance of PLA specimens [10, 11].

With the aim of bridging these gaps and delivering a comprehensive reference concerning the attributes and performance of PLA in the FDM 3D printing process, this review article endeavors to scrutinize the role and impact of PLA material in products created through FDM technology. By synthesizing existing research and conducting experimental analyses, this study strives to provide deeper insights into the structural and mechanical properties of PLA, the ramifications of printing parameters and infill patterns, and the industrial applications of products manufactured using PLA. The ultimate objective is to enhance our comprehension of PLA's attributes and performance and facilitate the effective utilization of FDM 3D printing technology. Within this article, the performance of PLA in the FDM process will be meticulously assessed through various parameter methodologies. It will explore the mechanical and structural characteristics of PLA based FDM printed parts and deliberate on the influence of printing parameters, infill patterns, and configurations on PLA's performance. Furthermore, it will delve into the industrial applications of PLA within FDM technology and contemplate potential future developments. This review aspires to serve as a valuable resource for 3D printing researchers, practitioners, and enthusiasts, imparting insights into the attributes and performance of PLA within the context of FDM 3D printing technology.

2. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) represents a significant subtype within the realm of three dimensional (3D) printing technology. This methodology employs the layer by layer fusion of thermoplastic materials to fabricate 3D objects [12, 13]. The process initiates with the creation or scanning of a digital model, which is then transformed into an STL file format. Subsequently, a 3D printer deposits liquefied material onto a platform via a heated print head, progressively constructing each layer. Following the completion of each layer, the material undergoes rapid cooling and solidification, ultimately culminating in the production of the intended object [14, 15]. FDM has garnered wide recognition as a pivotal 3D printing technology utilized across diverse applications, including prototyping, custom part manufacturing, industrial design, and various others [16-18]. Figure 1 provides a schematic depiction of a printer employing this technique. This manufacturing approach encompasses several crucial process parameters, the impacts of which are elucidated in the subsequent sections.

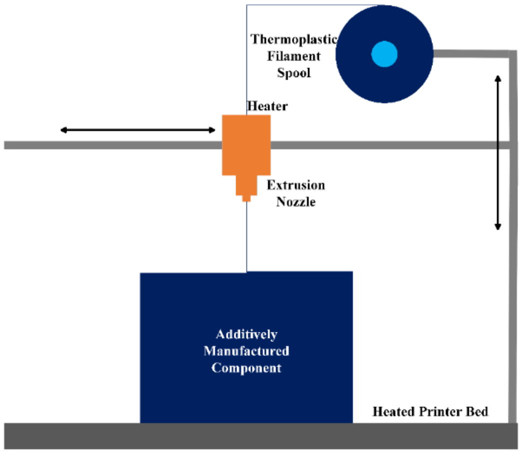

Figure 1. Schematic representation of FDM production

2.1. Manufacturing parameters

The Fused Deposition Modeling (FDM) process encompasses various process parameters that significantly impact both production efficiency and the ultimate characteristics of the final product. Crucial adjustable process parameters during the FDM process include layer thickness, build orientation, extrusion temperature, infill density, infill pattern, shell count, print speed, raster orientation, raster width, and post processing temperature (the latter being the final process parameter) [19]. The effects and significance of these fundamental process parameters are further elucidated below. Some schematic representations of FDM production parameters are presented in Figure 2.

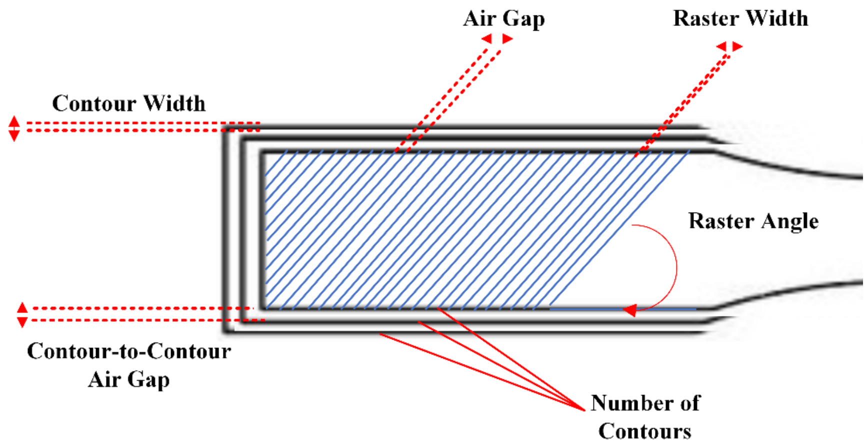

Figure. 2. Schematic representation of FDM production parameters for ASTM D638 model [20-22]

2.1.1. Layer thickness

Layer thickness is a critical process parameter in the domain of Fused Deposition Modeling (FDM) [23]. This parameter refers to the thickness of the layers formed during the extrusion process and is measured along the Z-axis, which corresponds to the vertical direction of the FDM apparatus. Typically, the layer thickness is smaller than the diameter of the extruder nozzle. It is a factor of paramount importance that exerts a significant influence on the results of FDM printing, requiring careful calibration. The determination of this parameter depends on various factors. Firstly, the diameter of the extruder nozzle plays a crucial role in determining the layer thickness; smaller nozzle diameters result in thinner layers. Furthermore, the material properties used in the process also impact the layer thickness [24, 25]. The material may require specific temperature and flow characteristics to achieve the desired layer thickness after extrusion.

Layer thickness has a profound impact on critical aspects of the final print, including surface roughness, durability, and level of detail. Therefore, the precise adjustment of this parameter is an essential aspect of achieving the desired outcomes in FDM printing.

2.1.2. Build orientation

The term "build orientation" represents a significant process parameter in 3D printing. It determines the direction or position in which an object will be created during 3D printing [26, 27]. In other words, it serves as a reference for how the object will be oriented and in which direction the layers will be constructed. Build orientation can influence the final properties, strength, smoothness, and printing time of an object [28, 29]. For example, if an object is printed horizontally, it may require more supports and result in a longer printing time, but the final product may have a smoother surface. On the other hand, printing in a vertical direction can reduce the need for supports, result in a faster printing time, but may increase surface roughness. Build orientation should be carefully selected based on the requirements of the design, material properties, and desired outcomes. Choosing the correct build orientation is a critical decision that can impact the successful implementation of the 3D printing process.

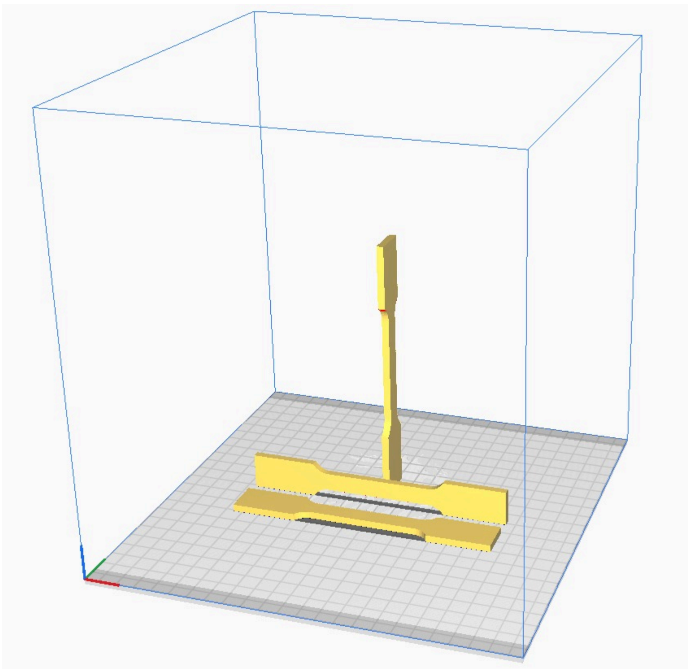

Figure 3. Schematic representation of three different build orientations for FDM production.

2.1.3. Raster angle/raster orientation

The term "raster angle" or "raster orientation" represents another crucial process parameter used during 3D printing [30, 31]. It determines the angle or direction in which the layers of an object will be positioned during printing. Raster angle or raster orientation defines how the layers will be drawn and how these lines will be placed on the surface of the object. This parameter can affect the mechanical properties, surface roughness, and aesthetic appearance of the object [32]. The raster angle can either increase or decrease the durability of an object and influence the final printing result. It also affects the printing time and material usage. Raster angle or raster orientation should be carefully chosen based on the requirements of the 3D printing design, material properties, and desired outcomes. This parameter is a critical decision for the accurate and optimized production of an object.

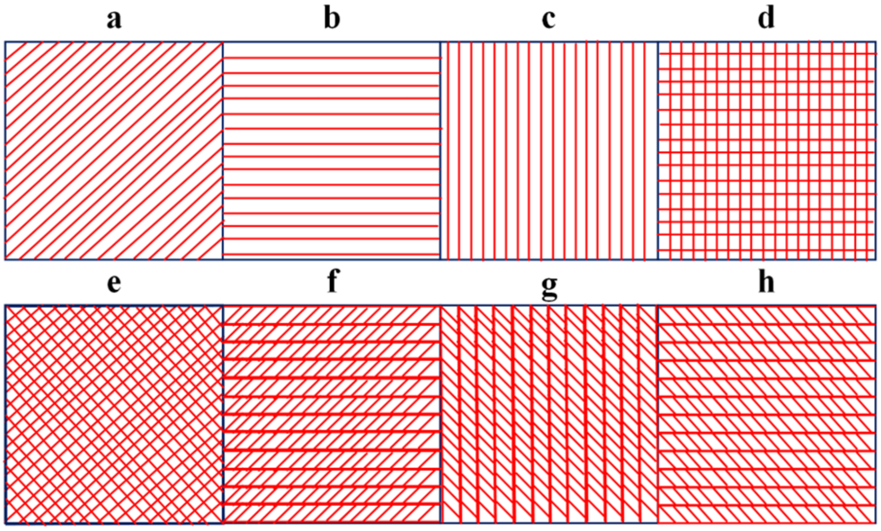

Figure 4. Schematic representation of different raster angles and orientations in FDM production

2.1.4. Layer height

Layer height refers to the thickness of the layers or slices used during the 3D printing process [33]. This parameter significantly affects how an object is constructed and influences the printing outcomes. Layer height determines the printing resolution. Thinner layer heights are used to achieve higher resolution and smoother surfaces, while thicker layer heights may result in faster prints with less detail [34]. 3D software or 3D printer settings allow users to adjust layer height according to their preferences. The selection of this parameter can vary depending on project requirements and design features. Choosing the right layer height is a critical decision with a significant impact on the results of 3D printing and should be adjusted carefully.

2.1.5. Air gap

The parameter of paramount significance in the context of Fused Deposition Modeling (FDM) process is the air gap. FDM operates on the principle of progressively depositing layers of materials, such as plastic filament or wire, during 3D printing. Therefore, it is imperative for these materials to fuse effectively. The air gap represents a pivotal parameter responsible for establishing the separation between layers, either facilitating a secure bond between them or preventing the entrapment of air [35, 36]. Improper calibration of the air gap can lead to observable imperfections, fissures, or feeble connections on the surfaces of produced objects. This can subsequently compromise the structural integrity and endurance of the final product. Furthermore, the incorrect adjustment of the air gap can impede the proper amalgamation of layers, thus affecting the surface texture of the end product. The precise configuration of the air gap parameter may fluctuate based on the characteristics of the printing material, printing velocity, and the design intricacies of the object. Effectively calibrating the air gap parameter can significantly augment the efficacy of the FDM process, resulting in sturdier, more refined, and superior quality objects. Hence, meticulous fine tuning of the air gap parameter assumes a position of profound importance in the realm of FDM 3D printing.

2.1.6. Extrusion temperature

Extrusion temperature is a vital process parameter in the Fused Deposition Modeling (FDM) process. This term refers to the temperature required to liquefy and layer thermoplastic filament or material used by a 3D printer for the proper creation of layers. Extrusion temperature is adjusted depending on the type and characteristics of the material being used. Correct melting and fluidity of the material at the right temperature ensure the firm bonding of layers and the desired quality of the print [37, 38]. Misadjustment of extrusion temperature can result in printing errors or material issues. Therefore, accurate adjustment of the extrusion temperature parameter is crucial for the quality and outcomes of FDM printing [39]. Manufacturer recommendations and trial and error methods can assist in achieving the correct extrusion temperature setting.

2.1.7. Print speed

Print speed, within the scope of 3D printing, represents the rate at which a 3D printer's print head fabricates objects, whether utilizing Fused Deposition Modeling (FDM) or other 3D printing methodologies [40]. This parameter exerts considerable influence over aspects such as inter layer bonding quality, printing duration, and the intricacies of the final product. Increased print speeds may lead to quicker results; however, an escalation in speed can have adverse effects on print quality, especially when producing complex or finely detailed objects. This may potentially result in heightened surface roughness or hinder the proper fusion of individual layers [41, 42]. The choice of an appropriate print speed should take into account factors such as design complexity, material properties, and the capabilities of the specific 3D printing equipment in use. Achieving the desired outcomes necessitates careful consideration of the optimal print speed. Consequently, the precise adjustment of the print speed parameter assumes paramount importance within the domain of 3D printing projects.

2.1.8. Infill pattern

Infill pattern refers to the pattern used to fill the interior of a 3D printed object [43-47]. This pattern determines how the material used to create the object's interior structure will be deposited and arranged. The infill pattern can affect the efficiency, strength, and material usage in the 3D printing process. For example, higher infill density (more fill) can make the object stronger but may require more material and extend printing time. Infill pattern can also influence the weight and cost of the object. 3D printer software typically offers various infill pattern options, including straight lines, hexagonal, square, and random patterns. The choice of infill pattern may vary depending on the intended use and design requirements of the object. Therefore, careful adjustment of the infill pattern parameter has a significant impact on the outcomes of 3D printing.

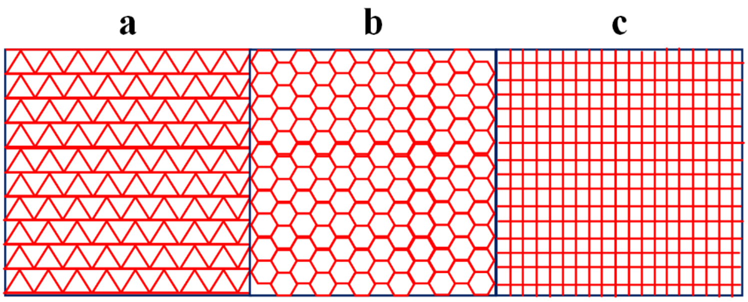

Figure 5. Schematic representation of different infill patterns

2.1.9. Infill density/interior infill percentage

This parameter determines how much of the interior of a 3D object will be filled. Infill density is usually expressed as a percentage (%) and represents the ratio of the filled portion of the object's interior structure to the total volume. This parameter balances material savings and object strength in 3D printing. Higher infill density results in a more solid interior structure, requiring more material but potentially increasing the object's strength. Lower infill density conserves material but may reduce the object's strength [44, 48]. 3D printer software often allows users to adjust infill density, giving designers control over the object's interior structure and strength. The choice of infill density may vary depending on the project's purpose, material cost, and printing time. Therefore, the selection of infill density is crucial and should be adjusted carefully.

2.1.10. Nozzle diameter

Nozzle diameter refers to the diameter of the print head at the tip of 3D printers. This parameter significantly affects how the filament or material used in 3D printing is extruded and impacts printing results. Nozzle diameter may vary between different 3D printer models and can be adjusted according to the user's preferences. Smaller nozzle diameters are typically used for achieving higher resolution and detailed prints, while larger nozzle diameters are preferred for faster printing with thicker layers [50, 51]. Nozzle diameter must match the selected material type and significantly influences printing results. The correct nozzle diameter selection affects the quality, speed, and outcomes of 3D printing. Therefore, 3D printer users often carefully evaluate and select the nozzle diameter that suits their project requirements. PLA (Polylactic Acid) filament commonly comes in diameters of 1.75 mm and 2.85 mm, with the choice depending on the specific 3D printer model and project requirements. For instance, numerous desktop 3D printers are designed to work with a 1.75 mm filament diameter, whereas certain industrial 3D printers utilize larger 2.85 mm filament diameters. Consequently, the selection of the PLA filament diameter is contingent upon the 3D printer chosen and the demands of the project.

2.1.11. Raster width

Raster width represents another significant process parameter used in Fused Deposition Modeling (FDM) or similar 3D printing processes. This term specifies the width at which the print head contacts the printing surface when creating the layers of a 3D object. Raster width determines how close or far apart layers will be, thereby affecting the printing outcome [55, 56]. Smaller raster widths can result in more detailed and smoother results but may extend the printing time and require more material. Larger raster widths can lead to faster printing and less material consumption but may increase surface roughness. Raster width should be adjusted based on project requirements, material properties, and printing speed. This parameter exerts a notable influence on the results of 3D printing and must be meticulously fine tuned to attain the desired equilibrium between quality and speed.

2.1.12. Bed temperature

In the context of 3D printing, the term 'bed temperature' refers to the temperature of the printing platform or bed [57, 58]. This parameter holds paramount significance in ensuring the successful execution of the printing process, and this importance arises from the following factors:

- Adhesion and Warping Control: Maintaining the print platform at a specific temperature ensures the proper adhesion of the 3D printing material (e.g., PLA or ABS) to the print bed. This helps prevent undesired detachment of the object and deformation. Additionally, temperature control aids in managing warping, a phenomenon in which the material contracts and distorts as it cools.

- Thermal Expansion Management: Keeping the print platform at a specific temperature ensures the proper adhesion of the material and the accurate bonding of layers. This enhances the quality of the final product and ensures the layers adhere firmly.

- Material Compatibility: Different 3D printing materials perform optimally at different bed temperatures. Therefore, the bed temperature should be adjusted based on the type of material used. For example, PLA material typically requires a bed temperature between 60-70°C, while ABS adheres at higher temperatures (100-110°C).

In conclusion, bed temperature is a critical parameter in FDM 3D printing processes to enhance print quality, prevent adhesion issues, and ensure material compatibility [59]. Properly adjusting this parameter is essential for achieving successful and robust 3D prints.

2.1.13. Number of contours

The term 'Number of Contours' denotes the quantity of layers forming both the internal structure and the outer surface of an object throughout the 3D printing process [60, 61]. The number of contours can impact the object's level of detail, durability, and final appearance. More contours can result in a sturdier and more detailed object but may increase print time and material consumption. Fewer contours can lead to faster prints and reduced material usage but may sacrifice detail. The number of contours can be adjusted through 3D software or printer settings. This parameter can vary depending on project requirements and design complexity, so selecting the right number of contours is crucial and should be done carefully.

2.1.14. Contour width

Contour width represents the width of the contours or perimeter layers created during a 3D object's printing process. Contour width determines how thick the outer surface layers of the object will be and how these contours will be formed. This parameter can influence the print's outcome, the object's durability, and its aesthetic appearance. A wider contour width can result in thicker outer surface layers, while a narrower contour width can yield more detailed and smoother surfaces. Contour width can be set through 3D software or printer settings and should be adjusted based on project requirements and design characteristics. Hence, the selection of contour width significantly influences the outcomes of 3D printing and necessitates meticulous calibration.

2.1.15. Contour to contour air gap

Contour to contour air gap refers to the distance between successive contour or perimeter layers of an object during the 3D printing process [62, 63]. It determines the proximity of one layer to the next, thereby influencing the outcome of the print, the structural integrity of the object, and its surface quality. A greater Contour to Contour Air Gap results in increased spacing between layers, whereas a smaller gap leads to tighter layer bonding. This parameter can be fine tuned through 3D software or printer settings, and its selection may vary depending on project specifications, material characteristics, and design intricacies. Consequently, the choice of the Contour to Contour Air Gap significantly impacts the 3D printing results and necessitates meticulous adjustment.

2.1.16. Feed rate

Feed rate refers to the rate of progression of a material or substance through a process or machine. This term is used in various industrial processes and manufacturing systems, including 3D printing [64, 65]. In the context of 3D printing, feed rate determines how filament or material is fed to the print head and how layers are built. This parameter affects printing speed and results [66]. A faster feed rate can expedite the printing process but may impact surface roughness and print quality. A slower feed rate may contribute to higher quality results but may extend printing time. Feed rate can be adjusted through 3D software or printer settings and may vary based on factors such as material type, layer height, and object complexity.

2.1.17. Printing speed

In the context of the 3D printing process, the term "Printing Speed" denotes the rate at which the print head of a 3D printer traverses while progressively constructing each layer of an object. This speed balances printing quality with fast results [40, 67]. Higher printing speeds can often lead to faster results but may result in rougher surfaces and reduced detail [68]. Slower speeds, on the other hand, can provide smoother, more precise, and higher quality prints but may extend printing time. Printing speed should be adjusted based on factors such as material type, layer height, and object complexity.

2.1.18. Pigmentation

The importance of pigmentation in production parameters, particularly in 3D printing processes like FDM, plays a critical role in product quality and aesthetics. Pigmentation not only determines the color and appearance of the final product but also has significant effects on its functionality and perceptibility [69]. Firstly, pigmentation can enhance the aesthetic appeal of a product. The choice of colors significantly affects the visual appeal and aesthetic value of an object. Colors can reflect the design language, intended use, and even brand identity of a product. Therefore, the correct color choice can increase the overall acceptance and attractiveness of a product. Additionally, pigmentation has an impact on the functionality of a product. Especially in industrial design, different colors can enhance the visibility of different components or functional areas. This can help users better understand and use the product. For example, marking different functional parts of medical devices with different colors can facilitate correct usage. Beyond this, pigmentation is essential for product identification. Color coding can help quickly and accurately identify specific parts or components. This can assist in error prevention and increased efficiency in processes such as maintenance, repair, or assembly. In conclusion, the role of pigmentation in FDM production parameters is versatile and critical for product quality. The color choice can enhance aesthetic value while improving functionality and identifiability. It is an important parameter to consider in design and manufacturing processes and can impact the end user experience.

2.1.19. Relative humidity

Relative humidity denotes the percentage of water vapor existing in the atmosphere at a specific temperature, serving as an indicator of atmospheric moisture levels [70, 71]. It constitutes a pivotal parameter necessitating scrutiny and regulation across various domains, encompassing material warehousing, the food industry, construction, meteorological prognostication, among others. This parameter delineates the concentration of water vapor within the air and exhibits variability contingent upon temperature. Typically, relative humidity is quantified as a percentage (%). For instance, a 50% relative humidity signifies that the air is halfway saturated with water vapor, while 100% relative humidity signifies complete saturation. Relative humidity assumes a position of significance in the context of Fused Deposition Modeling (FDM) for the following reasons:

- Material Drying: Filaments used in FDM, such as PLA or ABS, should be kept at low relative humidity levels during production. A humid filament can lead to undesired outcomes during printing, such as adhesion issues or surface quality degradation. Therefore, maintaining low relative humidity levels during filament drying and storage is crucial.

- Printing Quality: In the FDM process, it is essential for the material to flow and adhere correctly. High relative humidity can harm the internal structure of the filament, leading to printing problems. Conversely, low relative humidity can make the filament brittle. Hence, maintaining the correct relative humidity levels is vital for improving printing quality.

- Material Performance: Relative humidity can affect the performance of the material used in FDM. Relative humidity levels can influence properties such as durability, strength, and other physical attributes of the material. Paying attention to the relative humidity of the material can contribute to achieving the desired results.

In conclusion, controlling relative humidity in the FDM process is a critical factor that influences printing quality, material performance, and final results. Therefore, individuals involved in 3D printing should be attentive to relative humidity levels during the storage and usage of filaments.

2.2. Verification of production

Fused Deposition Modeling (FDM) technology employs a range of verification tests and parameters to evaluate the reliability and performance of 3D printing. These tests are crucial for assessing the quality and suitability of produced objects.

- Tensile Strength Test: This test measures how much force 3D printing material can withstand when subjected to tension. It is critical for evaluating product durability and strength. Similarly, the compression strength test determines how the material performs under compression forces.

- Dimensional Accuracy Tests: These tests assess how faithfully the printed object's dimensions match the intended design dimensions during the 3D printing process. They are used to ensure that the printed measurements fall within specified tolerances.

- Printing Time and Surface Roughness: Printing time and surface roughness are significant parameters that affect production efficiency and the final appearance and usability of the product. Printing time determines efficiency and production duration, while surface roughness influences the object's visual quality and usability.

- Bending Strength Test: The bending strength test evaluates how resistant an object is to bending forces. This is important for understanding how objects will behave under real world usage conditions.

All these tests are employed during the design and manufacturing phases to enhance the quality and efficiency of FDM 3D printing. Determining the appropriate parameters and routinely conducting these tests improve the quality of end products and mitigate potential issues. Figure 6 depicts a cause and effect diagram for FDM production parameters.

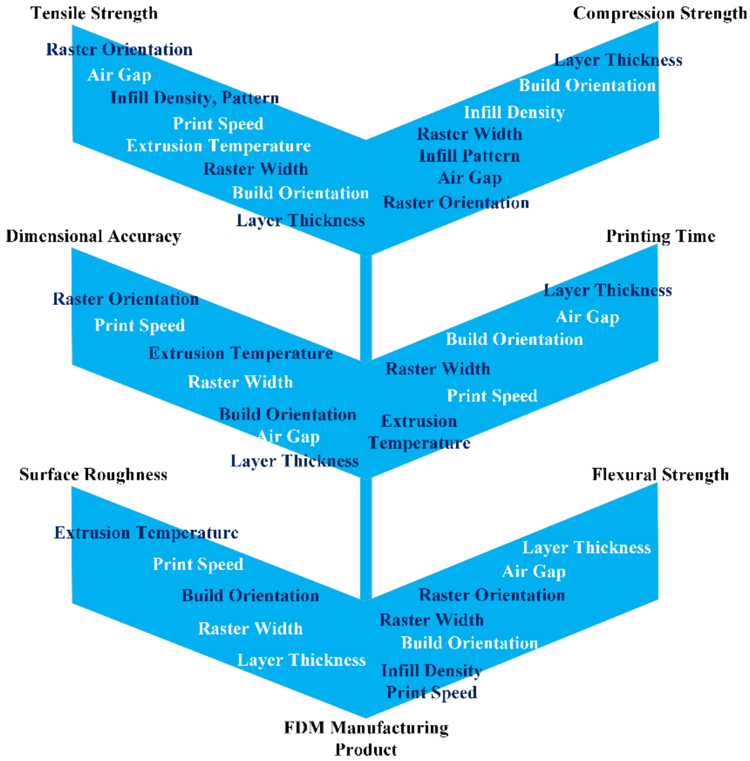

Figure 6. Fishbone Diagram for FDM Production Parameters [7]

3. Literature Review on Manufacturing Parameters

Research focused on the analysis of process parameters represents a critical area of investigation with the overarching objective of enhancing the efficiency of modern manufacturing processes while optimizing product quality. This line of research entails a systematic examination of fundamental process parameters used in various production techniques, including domains such as 3D printing, machining (including milling and turning), and additive manufacturing. The primary goal of such research endeavors is to comprehend, optimize, and contribute to the advancement of these processes, rendering them more sustainable and efficient. This is achieved by assessing the impact of these process parameters on the final product's quality and production efficiency.

In the specific context of 3D printing, process parameter analysis assumes critical importance as it aims to elucidate and enhance the effects of specific parameters during the layer by layer fabrication of objects. These parameters include, but are not limited to, layer height, printing speed, infill density, nozzle diameter, and temperature settings. These parameters are thoroughly examined within the scope of research, and their optimal combinations are determined through rigorous experimental studies and meticulous data analysis. This systematic approach serves to elevate overall result quality, enhancing print precision, durability, and surface finish.

In the field of process parameter analysis research, Design of Experiments (DOE) methodologies are commonly employed. These methodologies utilize statistical analysis and modeling techniques to discern the influence of various parameters on the final product's characteristics. Such investigations hold profound significance, not only for process refinement and quality enhancement but also for expanding the application horizons across diverse industrial sectors.

In summary, research efforts dedicated to the analysis of process parameters play a pivotal role in the quest to enhance efficiency, elevate quality standards, and foster innovation in contemporary manufacturing practices. This field of study is considered an indispensable component, propelling progress in critical domains such as manufacturing and 3D printing. Table 1 provides a comprehensive analysis of manufacturing parameters associated with the Fused Deposition Modeling (FDM) method using PLA material, as derived from the existing body of literature. It is noteworthy that all parameters listed in the table have undergone rigorous testing through tensile strength experiments.

Table 1. Literature analysis of manufacturing parameters of the FDM method with PLA material

Reference	Experimental Tested Parameters	Parameter Values
[1]	Layer Height Raster Angle/Raster Orientation	0.4 mm, 0.3 mm, 0.2 mm 0°, 45°, 90°
[9]	Layer Thickness Raster Angle/Raster Orientation	0.1 mm, 0.12 mm, 0.15 mm, 0.18 mm, 0.2 mm 0°, 18°, 45°, 72°, 90°
[5]	Build Orientation Layer Thickness	Flat (F), On-edge (O), Upright (U) 0.06 mm, 0.12 mm, 0.18 mm, 0.24 mm
[8]	Feed Rate Extrusion Temperature Relative Humidity Pigmentation	20 mm/sn, 50 mm/sn, 80 mm/sn 180°C, 190°C , 200°C, 220°C, 240°C %16, %50, %98 Pink, Green, Gray, Transparent
[72]	Infill Pattern Raster Angle/Raster Orientation	Concenctric, Grid, Triangle, Cross 3D, Zik Zak 0°, 45°, 90°
[73]	Infill Density Print Speed Extrusion Temperature Infill Pattern	%20, %100 100 mm/sn, 130 mm/sn 180°C, 220°C Gyroid, Cross 3D, Grid
[74]	Raster Angle/Raster Orientation Infill Density Print Speed Extrusion Temperature Layer Height Infill Pattern	175°, 180°, 185°, 205° %20, %50, %80, %100 70 mm/sn , 90 mm/sn , 120 mm/sn 170 mm/sn 175°C, 180°C, 185°C, 205°C 0.1 mm, 0.25 mm, 0.3 mm, 0.4 mm Diamond, Linear, Hexagonal
[75]	Extrusion Temperature Build Orientation Print Speed	200°C, 215°C, 220°C, 225°C, 235°C X, Y, Z, 45° 20 mm/sn, 40 mm/sn, 60 mm/sn
[76]	Layer Thickness Infill Pattern	0.150 mm, 0.175 mm, 0.200 mm Grid, Triangular, Honeycomb
[77]	Layer Thickness Extrusion Temperature Raster Angle/Raster Orientation Infill Density	0.1 mm, 0.2 mm 200°C, 220°C 0°, +45°, -45°, 90° %20, %40, %60
[78]	Raster Angle/Raster Orientation Layer Thickness Raster Width	0°, 45°, 90° 0.1 mm, 0.2 mm, 0.3 mm 0.5 mm, 0.6 mm, 0.7 mm
[79]	Infill Density Raster Angle/Raster Orientation Infill Pattern	%20, %100 0°, 30°, 45°, 90° Fast Honeycomb, Full Honeycomb Wiggle, Triangular, Grid , Rectilinear
[80]	Raster Angle/Raster Orientation Infill Density Print Speed	0° +45°, -45°, 90° %50, %75, %100 30 mm/sn, 60 mm/sn, 90 mm/sn
[81]	Raster Angle/Raster Orientation Infill Pattern	0°, +45°, -45°, 90° Straight, Honeycomb
[82]	Raster Angle/Raster Orientation	0°, 45°, 90°
[83]	Infill Pattern	Grid, Tri-hexagonal, Concentric
[84]	Layer Thickness Extrusion Temperature Infill Pattern	0.1 mm, 0.2 mm, 0.3 mm 205°C, 215°C, 225°C Cubic, Cubic sub Division, Quarter cubic

Table 1 presents a detailed literature analysis of various manufacturing parameters used in Fused Deposition Modeling (FDM) with Polylactic Acid (PLA) material, covering 17 different studies. The studies encompass a wide range of parameters such as layer height, raster angle/orientation, layer thickness, build orientation, feed rate, extrusion temperature, relative humidity, pigmentation, infill pattern, infill density, and print speed. These parameters show significant variability in their values. For instance, layer heights vary from 0.1 mm to 0.4 mm, extrusion temperatures from 175°C to 240°C, and print speeds from 20 mm/s to 170 mm/s. Despite the extensive range of parameters studied, some areas appear under researched. Traditional parameters like layer thickness and extrusion temperature are commonly focused, while factors like relative humidity and pigmentation are less explored. Future studies could benefit from focusing on these less explored parameters.

Overall, this analysis provides a comprehensive overview of the current state of research in FDM with PLA, highlighting extensive work in some areas while underlining the need for further research in others. Such studies are vital for advancing the field and enhancing practical applications of FDM 3D printing with PLA.

4. Discussion and Conclusion

Numerous experimental design techniques and optimization methodologies have been employed to determine the optimal combination of variables within the Fused Deposition Modeling (FDM) process. The primary objective is to either maximize or minimize specific desired outcomes. These approaches serve the crucial purpose of identifying the most influential process parameters, evaluating interactions among these parameters, and quantifying the extent to which each FDM process parameter influences the output variables. In the preceding section, we presented a comparative analysis of various experimental design techniques and optimization methods, emphasizing their distinct characteristics. Comprehensive review and analysis of the Fused Deposition Modeling (FDM) process, particularly using PLA material, underscore the significance of optimizing various process parameters to enhance part quality. The presented table details an array of experimental parameters tested in various studies, including layer height, raster angle/orientation, layer thickness, build orientation, feed rate, extrusion temperature, relative humidity, pigmentation, infill pattern, and print speed. These parameters are pivotal in determining the dimensional precision, surface texture, and overall quality of the FDM produced parts.

The analysis reveals a diverse range of parameter values, indicating the breadth of experimental approaches in the field. For instance, layer height values range from 0.06 mm to 0.4 mm, while extrusion temperatures span from 175°C to 240°C. Such variations highlight the complex interplay of these parameters in FDM printing and the necessity to understand their individual and combined effects.

Interestingly, certain parameters, such as relative humidity and pigmentation, have not been as extensively explored as others like layer thickness and raster orientation. This observation opens new avenues for research, suggesting that these lesser studied parameters might significantly impact the FDM process's efficiency and output quality.

Furthermore, the incorporation of diverse infill patterns and densities, as well as varying print speeds, suggests a rich area for further exploration in optimizing FDM processes. The table underscores the potential for enhancing part quality by meticulously adjusting these parameters.

The significance of this research lies in its critical role in shaping the overall efficiency and quality of FDM processes. The noteworthy findings presented in this compilation underscore the necessity for further exploration in the following domains:

- FDM primarily finds compatibility with thermoplastic materials, leading to a substantial focus on thermoplastics like PLA and ABS in FDM research. However, there has been an extension of studies to encompass other thermoplastics such as PETG, Nylon, and various composite materials.

- Some FDM process parameters have received more extensive scrutiny in comparison to others. Parameters like raster orientation/raster angle, layer thickness, FDM part build orientation, and raster width have garnered heightened attention. Conversely, parameters like internal infill patterns, infill densities, extrusion temperatures, contour counts, and others have received comparatively less analysis.

- The majority of optimization efforts have centered around the optimization of either a single output variable or multiple output variables, albeit independently rather than concurrently. Consequently, there exists a compelling need for additional research in the domain of multi objective optimization, which addresses the simultaneous optimization of multiple output variables.

- Many optimization techniques are rooted in statistical methodologies. An interdisciplinary research approach could involve the development of FDM process parameter optimization techniques utilizing image processing, Machine Learning, and Deep Learning.

- Furthermore, it is imperative to evaluate and model uncertainty at various stages of the FDM process.

This includes considering uncertainty factors within the optimization algorithms and inherent uncertainties in the mathematical modeling of the FDM process.

Conflict of Interest Statement

Authors of this paper state that there is no conflict of interest.

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