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A Review on Process Parameter Optimization in Material Extrusion Additive Manufacturing using Thermoplastic

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Abstract:- Material extrusion is one of the most commonly used additive manufacturing techniques which utilizes thermoplastics as the building material. The quality and performance of parts produced via material extrusion depends highly on the process parameters selected. This paper reviews the work done by various researchers on optimizing key process parameters like extrusion temperature, layer thickness, infill percentage, infill pattern etc. in material extrusion 3D printing using thermoplastics like PLA, ABS and nylon. The effects of these parameters on properties like surface roughness, dimensional accuracy, mechanical strength are discussed. Statistical tools like Taguchi method and response surface methodology that have been applied for parameter optimization are also reviewed. The review highlights the need for further process optimization studies considering part design, build orientation and post processing to unleash the full potential of material extrusion 3D printing..

Keywords:- *Additive Manufacturing, Material Extrusion, Process Parameters, Thermoplastics, Optimization.*

I. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, refers to a layer-by-layer fabrication technique used to manufacture physical objects directly from digital 3D model data. Material extrusion or fused deposition modeling (FDM) is one of the most commonly used AM processes, where a thermoplastic filament is selectively deposited through a heated nozzle to build 3D parts [1]. Material extrusion or fused deposition modeling (FDM) is one of the most widely used AM techniques and uses thermoplastics as the building material [2]. In material extrusion, a thermoplastic filament is unwound from a coil, heated to its semi-liquid state and extruded through a nozzle onto a build platform [3]. One of the key advantages of material extrusion AM is its capability to print functional prototypes and end use parts directly from digital 3D models using low-cost systems and widely available thermoplastic feedstock like polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and nylon [4].

However, the quality and performance of parts produced via material extrusion depend highly on the process parameters selected for the print job. Some of the important process parameters in material extrusion include extrusion temperature, layer thickness, infill percentage, infill pattern, print speed, cooling rate etc. [5]. Optimization of these parameters for a given part design, build orientation and material is crucial to achieve the desired mechanical properties, dimensional accuracy and surface finish. Many researchers have studied the effects of various process parameters on the printed part quality and carried out optimization experiments using statistical design of experiments. This paper aims to review the work done by different researchers on process parameter optimization in material extrusion 3D printing of thermoplastic.

II. LITERATURE REVIEW

A. Extrusion Temperature

Extrusion temperature is one of the most critical process parameters as it directly influences the viscosity and flow behavior of the extruded thermoplastic melts [6]. Higher temperatures lead to better bonding between deposited roads but if too high may cause material degradation, warpage and delamination [7]. Lee et al. [8] studied the effect of nozzle temperature on the mechanical properties and accuracy of PLA parts. They found that ultimate tensile strength and Young's modulus first increased and then decreased with increasing temperature in the range of 180-230°C. Shi et al. [9] optimized extruder temperature for ABS and PLA using Taguchi method and found that for ABS 180°C gave best mechanical properties while for PLA the optimum was 220°C.

B. Layer Thickness

Layer thickness determines the z-axis dimensional accuracy and surface roughness of printed parts [10]. Thinner layers result in higher resolution but increase print time significantly. Farahani et al. [11] found that 0.1mm layer thickness gave highest ultimate tensile strength and Young’s modulus for PLA parts compared to 0.15 and 0.2mm. Jiang et al. [12] also observed a decline in tensile strength of ABS specimens with increasing layer thickness from 0.1 to 0.3mm. Chacon et al.[13] used response surface methodology to optimize layer thickness of ABS parts and obtained the optimum as 0.18mm considering

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strength, accuracy and printing time

C. Infill Percentage and Pattern

Infill refers to the density of the interior solid structure of a 3D printed part. Higher infill leads to improved strength but increased material usage and printing time [14]. Different infill patterns like lines, grid, triangle and honeycomb have been studied. Vaezi et al. [15] observed highest flexural strength for 30% honeycomb infill PLA specimens compared to other patterns and percentages. Ahn et al. [16] optimized ABS infill using Taguchi design and determined the optimum as 25% rectilinear pattern. Moon et al. [17] also obtained 25% infill as the optimum design for maximum flexural strength of nylon parts with grid pattern being superior.

D. Cooling Rate

Rapid cooling enhances interlayer adhesion while slow cooling allows better stress relaxation resulting in less warpage [18]. Control over cooling rate can be achieved by modifying print bed temperature, part fan speed and using polymeric additives like impact modifiers. Wang et al. [19] studied the effect of print bed temperature on ABS dimensional accuracy and found lower print bed temperatures below glass transition temperature promoting adhesion between layers without causing warpage or deformation. Wei et al. [20] developed a multi-objective optimization strategy to simultaneously maximize tensile strength and dimensional accuracy of ABS parts by controlling print fan speed.

III. MATERIALS

Thermoplastic polymers are most commonly used as build materials for material extrusion 3D printing due to their ease of processing, low melting points, and low cost. Some of the key thermoplastics utilized include:

A. Polylactic Acid (PLA):

PLA is a biodegradable and renewable thermoplastic derived from corn starch, sugar cane or other plant-based materials [21]. It has high strength and stiffness comparable to petroleum-based plastics. PLA provides good dimensional accuracy, clarity and surface finish in 3D printed parts. However, it has low heat deflection temperature, limiting its use in high-heat applications. Typical extrusion temperature for PLA ranges between 180-220°C.

B. Acrylonitrile Butadiene Styrene (ABS):

ABS is a general purpose engineering plastic with good impact strength even at low temperatures [22]. It offers balanced mechanical properties and dimensional stability during printing. ABS also provides good layer adhesion. However, it emits toxic fumes during printing and requires an enclosed print workspace. Extrusion temperatures for ABS are usually in the range of 210-250°C.

C. Polyetherimide (PEI):

PEI is a high performance thermoplastic used in aerospace and automobile applications due to its exceptional dimensional stability and strength at high temperatures [23]. It exhibits high heat deflection temperature of around 250°C. However, PEI filaments are expensive compared to other materials. Extrusion temperatures also need to be higher at around 340-360°C for PEI.

D. Nylon:

Nylons or polyamides refer to a family of plastics including Nylon 6, Nylon 12, Nylon 11 etc. commonly used for AM [24]. They offer good mechanical properties, wear and chemical resistance. Nylon exhibits layer adhesion issues during printing but provides strong and elastic final parts. Typical extrusion window is between 230-260°C for different nylon grades.

E. Thermoplastic Polyurethane (TPU):

TPU provides rubber-like flexibility, abrasion resistance and biocompatibility [25]. It is suitable for applications requiring flexible parts. However, standard FDM printers need modifications to process semi-crystalline TPU filaments. Extrusion is carried out between 220-240°C generally.

The selection of a thermoplastic build material greatly influences the selection of process parameters in material extrusion 3D printing. Properties like glass transition temperature, crystallinity, viscosity determine the optimal extrusion temperature and other settings.

IV. CHALLENGES AND DEFICIENCIES

Some key deficiencies and challenges highlighted based on the literature review include:

- Lack of standardized test geometries and evaluation protocols to quantify effects of complexity
- Process models inadequate in capturing anisotropy induced in complex parts
- Optimization approaches not systematically addressing interactions between multiple parameters
- Limited quantification of defects like voids, warping and residual stresses in overhanging walls
- Support structure optimization focused on removal rather than balance of mechanical properties
- Incompatibility between slicing algorithms and intricate internal architectures
- Uncertainty in scaling parameterized approaches developed for simple shapes
- Absence of design guidelines incorporating AM induced limitations of complex parts
- Deficiencies in post-processing techniques to enhance properties of complex features
- Data scarcity on mechanical reliability of lattice structures, tight toleranced parts
- Quality assurance challenges for certifying safety/quality of complex medical implants

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V. CONCLUSION

This paper reviewed the work reported in literature on optimization of key process parameters for material extrusion 3D printing using thermoplastics. Parameters like extrusion temperature, layer thickness, infill percentage and pattern, cooling rate were identified to have significant effects on part properties. Statistical techniques like Taguchi and Response surface methodology have been effectively applied for single and multi-variable optimization studies. There is still scope for further research considering part design, advanced thermoplastics, build orientations and incorporation of post- processing methods to enhance mechanical performance and geometric fidelity of manufactured parts. Overall process optimization could help leverage the full capabilities of material extrusion additive manufacturing.

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