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Multi-Objective Optimization of FDM Process Parameters for Three Materials

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***Abstract*— This project focuses on the multi-objective optimization of process parameters in Fused Deposition Modeling (FDM), a widely used 3D printing technology. The goal is to study and enhance the performance of three different FDM materials—PLA Plus, PVA, and HIPS—by adjusting key slicing parameters such as layer height, print speed, infill density, and print temperature. A standardized test specimen (ASTM D638 Type VI) will be printed under varied conditions, followed by break tests to evaluate strength and an analysis of print time. By examining the relationship between slicing parameters and printed part performance, the project aims to identify optimal settings that achieve a balance between fast printing and mechanical strength. The outcome is expected to contribute valuable data for improving print efficiency and part quality in practical 3D printing applications.**

Keywords- Fused Deposition Modeling (FDM), Process Optimization, Slicing Parameters, ASTM D638

INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, has revolutionized modern manufacturing by enabling the production of complex geometries, customized parts, and rapid prototyping with relatively low material waste. Among the various AM technologies, Fused Deposition Modeling (FDM) is one of the most widely adopted methods due to its cost-effectiveness, material versatility, and ease of operation. FDM builds parts layer by layer by extruding thermoplastic filaments, making it ideal for both industrial and academic applications.

However, the mechanical performance and print efficiency of FDM-fabricated components are significantly influenced by a variety of process parameters, also known as slicing parameters. These include layer height, print speed, infill density, and nozzle temperature, among others. These parameters not only affect the dimensional accuracy and surface finish of printed parts but also determine critical performance metrics such as tensile strength, durability, and printing time.

Recent studies have shown that there is no universal set of optimal parameters, as the ideal combination varies depending on the material type and application requirements. Therefore, a multi-objective optimization approach is required to strike a balance between mechanical strength, print speed, and material efficiency. This project specifically focuses on three FDM materials with diverse mechanical and chemical characteristics—PLA Plus (Polylactic Acid Plus), PVA (Polyvinyl Alcohol), and HIPS (High Impact Polystyrene). These materials were selected for their distinct properties: PLA Plus for rigidity and biodegradability, PVA for water solubility and support structure applications, and HIPS for impact resistance and ease of post-processing.

To evaluate the performance of each material under different process settings, a standard tensile test specimen (ASTM D638 Type VI) will be designed and printed using a combination of slicing parameters. Break tests will be conducted to assess maximum tensile stress, while print time will be recorded for efficiency analysis. This structured methodology allows for a comparative study that aims to identify the optimal set of process parameters for each material, addressing both performance and productivity.

The insights gained from this project will serve as a valuable reference for researchers, engineers, and practitioners seeking to improve FDM-based manufacturing processes. Furthermore, the study contributes to the broader field of additive manufacturing process optimization, where tailoring print settings to specific materials is essential for achieving high-performance parts.

I. LITERATURE REVIEW

Fused Deposition Modeling (FDM) is one of the most commonly used additive manufacturing technologies due to its affordability, material availability, and ease of use. However, the quality and performance of printed parts are significantly influenced by multiple process parameters. Consequently, a growing body of research has been focused on understanding and optimizing these parameters to enhance mechanical properties, dimensional accuracy, and print efficiency.

1. Influence of Process Parameters on Mechanical Properties

Mohamed et al. (2015) conducted a comprehensive review on the optimization of FDM process parameters, highlighting that parameters such as layer thickness, print speed, raster angle, and infill density have a direct impact on tensile strength, surface roughness, and part durability. The study concluded that no single parameter universally enhances all properties, and thus, a trade-off often exists between quality and productivity [2].

Chacón et al. (2017) experimentally investigated PLA parts fabricated via FDM and found that lower layer heights and higher infill densities lead to improved tensile strength. However, these settings significantly increase the print time, emphasizing the need for multi-objective optimization strategies [4].

2. Material-Specific Behavior

Different thermoplastic materials behave differently under the same printing conditions. PLA, known for its ease of printing and biodegradability, shows good stiffness but is brittle under tensile loads. PVA, a water-soluble material often used for support structures, has limited structural strength and behaves differently under thermal stress. HIPS, on the other hand, offers high impact resistance and dimensional stability but requires specific temperature control to avoid warping.

Domingo-Espin et al. (2015) studied the mechanical performance of polycarbonate (PC) printed with FDM and emphasized that material-specific parameter tuning is essential, as default slicing profiles often fail to deliver optimal results across different materials [5].

3. Optimization Techniques and Multi-Objective Approach

Several researchers have applied statistical and optimization methods to determine optimal process settings. Rajpurohit and Dave (2018) utilized Taguchi and ANOVA techniques to optimize layer height and infill density for ABS parts, showing that mechanical strength can be significantly improved through controlled experimentation [6].

In terms of multi-objective optimization, Boschetto and Bottini (2014) proposed the use of desirability functions to balance multiple output metrics like surface finish and strength. Their results demonstrated the potential of optimization frameworks to improve part quality without drastically increasing build time [7].

4. Standard Testing and Evaluation Methods

Most studies use ASTM D638 standards for tensile testing to evaluate the mechanical performance of printed parts. The Type IV and Type V specimens are commonly used for polymer characterization due to their well-defined geometry and consistent break location, making them suitable for comparative analysis.

Torrado and Roberson (2016) analyzed the anisotropy of FDM parts and emphasized the importance of consistent test specimen geometry and raster patterns for repeatable results [8].

II. METHODOLOGY

1. **Design Selection**:

A standard design (ASTM D638 Type VI) will be chosen for printing. The design should be simple enough to conduct break tests.

2. **Printing:**
   1. Print 27 copies of the selected design, with 9 copies Print temperature.
   3. Document the slicing parameters used for each print.

3. **Testing:**
   1. Conduct a break test on each printed part to measure the maximum stress it can handle. This test will help determine the strength of each part.
   2. Record the print time for each part.
4. **Analysis:**
   1. Compare the results to identify trends and correlations between slicing parameters and the three main performance metrics (print time and strength).
   2. Determine the optimal set of slicing parameters for each material that balances fast printing and high strength.

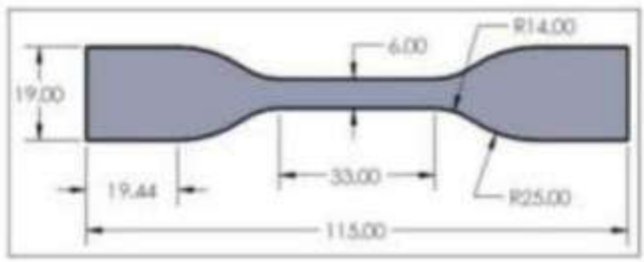
III. OBJECTIVES:

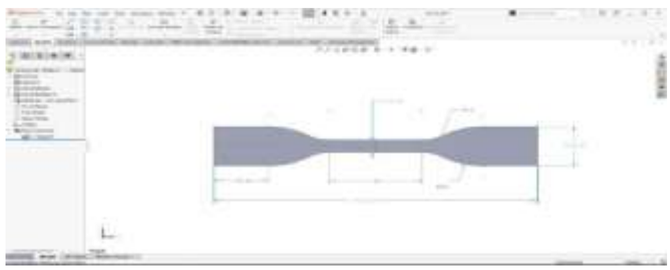
1. To study the influence of key slicing parameters on print time and strength.
2. To optimize printing parameters for three different FDM materials.
3. To evaluate mechanical properties through break (tensile) tests.

Materials And Methods

A. Materials Used -
   1. PLA Plus
   2. PVA
   3. HIPS

B. Design of Experiment : Specimen design: ASTM D638 Type VI





C. Parameters Varied

Parameters	Layer Height	Print Speed	Infill Density	Temp
	0.178	55	10	210
Levels	0.2	60	20	215
	0.25	65	30	220

D. Printing Process:

I. Combinations Of Parameters:

Experiment	Materials	Layer height	Print speed	Infill density	Temp
1	PLA PLUS	0.178	55	10	210
2	PLA PLUS	0.178	60	20	215
3	PLA PLUS	0.178	65	30	220
4	PLA PLUS	0.2	55	20	220
5	PLA PLUS	0.2	60	30	210
6	PLA PLUS	0.2	65	10	215
7	PLA PLUS	0.25	55	30	215
8	PLA PLUS	0.25	60	10	220
9	PLA PLUS	0.25	65	20	210

Similarly for PVA and HIPS materials.

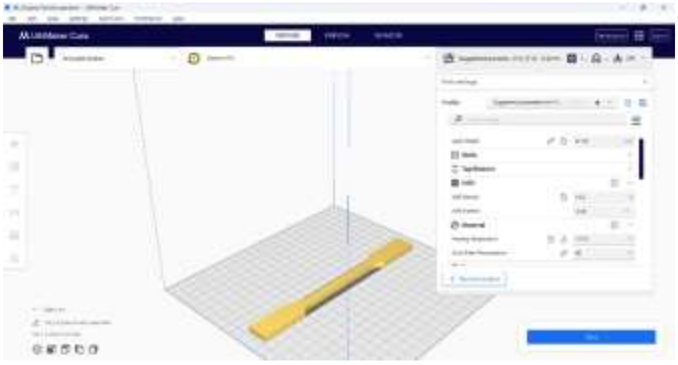
Experiment	Materials	Layer height	Print speed	Infill density	Temperature
1	PVA	0.178	55	10	210
2	PVA	0.178	60	20	215
3	PVA	0.178	65	30	220
4	PVA	0.2	55	20	220
5	PVA	0.2	60	30	210
6	PVA	0.2	65	10	215
7	PVA	0.25	55	30	215
8	PVA	0.25	60	10	220
9	PVA	0.25	65	20	210

Experiment	Materials	Layer height	Print speed	Infill density	Temperature
1	HIPS	0.178	55	10	230
2	HIPS	0.178	60	20	235
3	HIPS	0.178	65	30	240
4	HIPS	0.2	55	20	245
5	HIPS	0.2	60	30	250
6	HIPS	0.2	65	10	255
7	HIPS	0.25	55	30	260
8	HIPS	0.25	60	10	235
9	HIPS	0.25	65	20	245

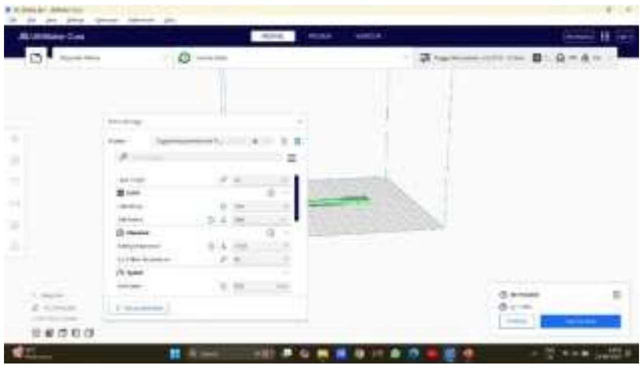
II. 3D printer model used : Any Cubic Kobra

The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the object is created. Each of these layers can be seen as a thinly sliced cross-section of the object. 3D printing is the opposite of subtractive manufacturing which is cutting out / hollowing out a piece of metal or plastic with for instance a milling machine

III. Slicing software : UltiMaker Cura



Make Changes for all Specimens



IV. Procedure to print 3D parts

3D printing is a process that creates three-dimensional objects from a digital model. It's often called additive manufacturing (AM) because the objects are built by adding successive layers of material, one on top of the next. Conventional manufacturing uses subtractive methods where the desired shape is created by cutting material away from a solid block. 3D printing is less wasteful because material is only added where it's needed to create the part.

A 3D printer is the machine that builds the part. 3D printers differ based on the type of printing technology used and the size of the parts they can build. To make the part, the printer gets its "instructions" from a CAD model and software "slices" the CAD model into virtual layers. The printer then applies material where it's needed to build each layer until the object is completed. From rapid prototyping to manufacturing to realistic medical modeling, 3D printing opens the door to increased efficiencies and broader business opportunities. 3D printing frees you from traditional manufacturability constraints because your designs aren't limited by the restrictions of conventional. .machine and mold tools. You can make things that often can't be made at all with conventional tools, so you can optimize and create prototypes, tools, medical models and functional parts much more quickly and for a lower cost.

Testing on UTM machine:

The set-up and usage are detailed in a test method, often published by a standards organization. This specifies the sample preparation, fixturing, gauge length (the length which is under study or observation), analysis, etc.

The specimen is placed in the machine between the grips and an extensometer if required can automatically record the change in gauge length during the test. If an extensometer is not fitted, the machine itself can record the displacement between its cross heads on which the specimen is held. However, this method not only records the change in length of the specimen but also all other extending / elastic components of the testing machine and its drive systems including any slipping of the specimen in the grips.

Once the machine is started it begins to apply an increasing load on specimen. Throughout the tests the control system and its associated software record the load and extension or compression of the specimen.

IV. RESULTS

Ultimate Tensile Strength (UTS)- The ultimate tensile strength of a material is an intensive property; therefore, its value does not depend on the size of the test specimen. However, depending on the material, it may be dependent on other factors, such as the preparation of the specimen, the presence or otherwise of surface defects, and the temperature of the test environment and material.

Some materials break very sharply, without plastic deformation, in what is called a brittle failure. Others, which are more ductile, including most metals, experience some plastic deformation and possibly necking before fracture.

Actual Time Required And Ultimate Tensile Strength

Material	Time Required	UTS (MPa)
PLA plus 1	34min 21sec	36.26
PLA plus 2	38min 39sec	38.50
PLA plus 3	37min 32sec	38.52
PLA plus 4	36min 48sec	35.03
PLA plus 5	37min 04sec	36.89
PLA plus 6	31min 55sec	34.77
PLA plus 7	34min 12sec	33.87
PLA plus 8	25min 07sec	33.20
PLA plus 9	28min 48sec	37.08

Material	Time Required	UTS (MPa)
PVA 1	38min 40sec	20.39
PVA 2	37min 48sec	21.64
PVA 3	37min 15sec	22.08
PVA 4	36min 36sec	11.44
PVA 5	36min 14sec	10.26
PVA 6	31min 35sec	09.16
PVA 7	32min 13sec	09.21
PVA 8	30min 30sec	10.51
PVA 9	29min 12sec	9.86

Material	Time Required	UTS (MPa)
HIPS 1	46min 16sec	14.00
HIPS 2	45min 55sec	14.30
HIPS 3	40min 01sec	15.81
HIPS 4	44min 40sec	14.58
HIPS 5	44min 24sec	15.13
HIPS 6	40min 28sec	15.22
HIPS 7	39min 13sec	17.09
HIPS 8	27min 19sec	15.07
HIPS 9	32min 01sec	16.05

V. CONCLUSION

In this project we have taken 5 parameters being material, wall thickness, layer height, infill density, infill pattern with 3 variables. By using taguchi method for optimization we have created 27 specimen parameters by using L27 array.

The specimen number 3 (material-PLA plus, wall thickness-1mm, infill pattern- cubic, infill density- 30%, layer height-0.178mm, temperature-220) exhibits highest ultimate tensile strength among 9 PLA material.

The specimen number 3 (material-PVA, wall thickness-0.8mm, infill pattern- triangular, infill density- 30%, layer height-0.178mm, temperature-220) exhibits highest ultimate tensile strength among 9 PVA material.

The specimen number 7 (material-HIPS, wall thickness-0.712mm, infill pattern- cubic, infill density- 30%, layer height-0.25mm, temperature-215) exhibits highest ultimate tensile strength among 9 HIPS material.

The specimen number 3 (material-PLA plus, wall thickness-1mm, infill pattern- cubic, infill density- 30%, layer height-0.178mm, temperature-220) exhibits highest ultimate tensile strength among all 27 specimens.

The valuable data collected during this project can also act as reference for further studies or rapid prototyping on UltimakerCura printer as it is evident from test conducted in the laboratory and the data gathered.

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