Fusion Deposition Modelling and Parametric Optimization for Warping Mitigation in 3D Printing of Polylactic Acid Thermoplastic

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Abstract. The recent proliferation of 3D printing technology, particularly in rapid prototyping, has been remarkable. Additive manufacturing techniques construct 3D objects layer by layer or along specific paths. This study focuses on examining and mitigating warping deformations in Fused Deposition Modelling 3D printed objects, with a specific emphasis on varying process parameters. The optimization technique employed is response surface methodology, with nozzle temperature and print speed as continuous factors, and bed temperature as a categorical factor. The research investigates the impact of different nozzle temperatures (185°C, 200°C, and 210°C), printing speeds (15 mm/s, 45 mm/s, and 55 mm/s), and bed temperatures (27°C and 50°C) during the FDM 3D printing process. Experimental findings identify optimal conditions for minimal warping deformation. Notably, the lowest warping deformation value was achieved at a nozzle temperature of 200°C, print speed of 15 mm/s, and bed temperature of 27°C. This research highlights the complex interaction between nozzle temperature, printing speed, and other parameters in controlling warping deformations during FDM 3D printing, offering valuable insights for enhanced printing outcomes.

Keywords: 3D printing, Additive manufacturing, Fused deposition modelling, Warping deformations.

1 Introduction

Additive manufacturing (AM) stands as a burgeoning technology that empowers the manufacturing of intricate objects. This innovative technology possesses the capability to 3D print nearly any material, spanning metals and their alloys, ceramics, polymers, biological substances, and more. This versatility bestows a broad spectrum of product possibilities across various engineering domains, including the automotive, aerospace, civil engineering, medical, energy, and sports sectors. Among the present 3D printing methods, Fused Deposition Modelling (FDM) takes the lead as the most extensively employed technique. It delivers cost-

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effective manufacturing solutions that cater to a diverse array of consumers. Both liquid-based and powder-based techniques find application in the generation of polymer-based materials suitable for additive manufacturing. The polymers employed in these processes generally encompass thermoplastic filaments, resins, or powders. The economical construction of FDM printers is attributed to their mechanical simplicity, rendering intricate and costly components unnecessary. Consisting of three axes directed by three stepper motors, these printers are further equipped with a print head and print bed. These components are positioned in a configuration that grants three degrees of freedom along these axes. This approach contributes to objects with a finer level of detail compared to stereolithography. Warping issues represent a common challenge encountered within the realm of 3D printing. This phenomenon refers to the undesirable deformation or distortion of a printed object's shape during or after the printing process. It arises due to various factors and can have detrimental effects on the final print's quality and accuracy. A primary contributor to warping is material shrinkage, particularly evident in thermoplastic materials like ABS and PLA, as they cool down and contract. To combat this, the application of a heated build platform is advisable, as it promotes better adhesion and diminishes contraction-induced detachment. Uneven cooling during layer deposition also plays a role, resulting in differential contractions between layers and contributing to warping. Employing controlled cooling mechanisms, such as fans and appropriate cooling settings, can help alleviate this issue. Inadequate initial layer adhesion, influenced by factors like print orientation, supports, and environmental conditions, can further exacerbate warping. By focusing on optimizing print settings, orientation, and environmental controls, manufacturers can effectively mitigate the challenges posed by warping, ultimately leading to enhanced 3D printing outcomes.

2 Literature Survey

The most widely used 3D printing process is fused deposition modelling (FDM), which offers superior mechanical, thermal, and chemical resistance [1, 2]. Early in the 1990s, Stratasys, Ltd., in the USA, commercialised the first 3D product using FDM, which had been created in the late 1980s [3]. The majority of earlier studies on FDM 3D printing go into great detail about the procedure [4, 5]. One of the most widely used methods varies slightly depending on the type of sources used and is provided below. Regarding this technology, the consensus among academics suggests that the long-fibre thermoplastic (LFT) polymer filament is heated and extruded through a heated circular nozzle to a temperature nearing its point of fusion. Subsequently, it is deposited in a semi-molten state to achieve the desired shape. Internal strains may result in warping deformations at the corners of LFT as it gets cold [6]. The production process of plastic components for various industrial applications has undergone a significant revolution. Additionally, it has been increasingly replacing traditional subtractive manufacturing techniques, these processes often eliminate as much as 95% of the raw material to manufacture the final component. [7-9]. The process of combining materials to make a three-dimensional model often happens layer-by-layer or path-by-path as the material is moulded into layers is known as additive manufacturing (AM), also known as "3D Printing". With the development of additive manufacturing (AM), it has become considerably simpler to produce a 3D physical product of any shape straight from a computer-aided design (CAD) model utilising a quick, flexible process and automated system [10]. Even though the intricacy of the plastic component is great, this achievement was previously considered impossible and substantially cuts down the product's manufacturing lead time by up to 50%. [11]. One of the drawbacks of the plastic filament material extruded from the circular nozzle of the open-source FDM 3D printer is its tendency to twist and detach from the platform. Numerous researchers have drawn attention to the warp deformation concerns with the FDM 3D printer [7, 12, 13]. To obtain high-quality FDM 3D printing parts, the best FDM 3D printer process parameter setting must be found because of the possibility of warping deformation caused by the various FDM 3D printer process parameter settings. In the FDM process, a material is layer by layer extruded from a temperature-controlled nozzle onto a heated table to create the desired part [14,15]. By adjusting the printer's parameters, a multitude of factors can be regulated, encompassing layer thickness, support angle, extrusion temperature, platform temperature, print speed, extruder flow ratio, nozzle distance, infill type, infill density, surface layers, supports, seam type, and fan speed. All of these factors are crucial for determining print quality. Stringing issues are the most frequent issues pertaining to printer settings. When the nozzle is not extruding, it leaves behind little threads of polymer that are what cause this to happen. When constructing parts that are separated by small gaps, this flaw may remain. For some materials, oozing-related strings may be eliminated mechanically or chemically by surface treatment. On the other hand, interior features and joints may make that difficult to achieve [16]. When using the FDM printing technique, several factors can impact the print quality. Some of them can be learnt and comprehended through experiences [17]. To our knowledge, no publication systematically evaluates the warping deformation of FMD 3D parts made by AM with polylactic acid (PLA) filament at each corner, where the independent variables are printing temperatures between 185°C and 210°C and printing speeds between 15 mm/s and 55 mm/s for validating the results. To our knowledge, no publication systematically evaluates the warping deformation of FMD 3D parts made by AM with polylactic acid (PLA) filament at each corner, where the independent variables are printing temperatures between 185°C and 210°C and printing speeds between 15 mm/s and 55 mm/s for validating the results. This paper's primary goal is to examine how the warping deformation was impacted by the FDM 3D printer process parameters. To minimise the warping deformation, the best process parameter values must be determined. Additionally, to achieve a very low percentage of error between the real value (as an input parameter) and measure value (as an output parameter), it is necessary to determine the warping deformation at each corner of the FDM 3D parts as well as the overall warping deformation of the system.

3 Machine and Materials

3.1 Machine

Fig. 1. Creality Ender 3D Printer

The manufacturer of the printer is Creality 3D, based in China. The model is Ender 3 is shown in Figure 1, utilizing FDM (Fused Deposition Modeling) technology. It has a build volume of 220mm x 220mm x 250mm and overall dimensions of 440mm x 410mm x 465mm. The printer is equipped with a heated bed with a textured surface. It supports various filament materials including PLA, ABS, PETG, and TPU with a diameter of 1.75mm. The printer offers a resolution of 0.1mm and features a single extruder. Connectivity options include USB and SD card.

3.1 Material

Thermoplastic filaments are the primary materials utilized in the majority of Fused Deposition Modeling (FDM) machines. Among these, Acrylonitrile Butadiene Styrene (ABS) and Polylactide (PLA) are commonly used in 3D printing. PLA, the focus of this experiment, undergoes modifications before being used as a filament material. Although PLA has a melting temperature range of 130°C to 180°C, the PLA used in 3D printing is altered. PLA filament material possesses commendable mechanical properties, with an elastic modulus (E) ranging from 3.2 to 3.7 GPa and a tensile strength (TS) of approximately 50 MPa. PLA can withstand temperatures up to 110°C. Blending the polymer with PDLA (poly-D-lactide) can increase the melting temperature by approximately 40–50°C and elevate the heat deflection temperature from around 60°C to as high as 190°C. These characteristics highlight PLA's versatility and its potential for customization to meet specific application requirements in 3D printing.

4 Experimental Work

The specimen was designed using SolidWorks software, with dimensions of 100mm in length, 30mm in width, and 5mm in height. It was saved in STL format for compatibility with slicer software, such as Ultimaker Cura 4.12.1, which generates G-code files necessary for FDM printers. Before printing, the print bed was levelled and preheated to ensure proper filament adhesion.

Based on literature findings, three key parameters affecting warping were identified: Nozzle temperature (185°C, 200°C, and 210°C), Print Speed (15 mm/s, 45 mm/s, and 55 mm/s), and Bed temperature (27°C and 50°C). Similarly, for the warping tests, variations in Print speed, Nozzle temperature, and bed temperature were explored, keeping other parameters constant. Response Surface Methodology (RSM) was employed for optimization, utilizing the Central Composite Method. The methodology involved two continuous factors (nozzle temperature and print speed) and one categorical factor (bed temperature). A total of 26 different combinations of process parameters were considered, with 8 repetitions, resulting in 18 unique sets of process parameters. The design of experiments is detailed in Table 1. The parts fabricated using different parameter combinations are illustrated in Figure 2.

After FDM 3D parts were fabricated, they were allowed to cool to room temperature before measurements were taken directly after removal from the platform. Dimensions of the test bar at each edge and in the centre were measured using a digital screw gauge. Each dimension was measured at least three times, and the average was calculated to determine deviation. The deviation is detailed in Table 2.

Table 1. Design of Experiments

S.No	Nozzle Temperature°C	Print Speed mm/s	Bed Temperature °C
1	200	45	50
2	200	30	50
3	210	30	27
4	210	15	27
5	200	30	27
6	200	15	50
7	210	45	50
8	200	30	27
9	200	30	50
10	200	30	27
11	210	15	50
12	185	30	27
13	185	45	27
14	200	30	50
15	200	30	27
16	210	30	50
17	185	15	50
18	200	15	27
19	200	30	27
20	210	45	27
21	185	30	50
22	200	30	50
23	185	45	50
24	200	30	50
25	185	15	27
26	200	45	27

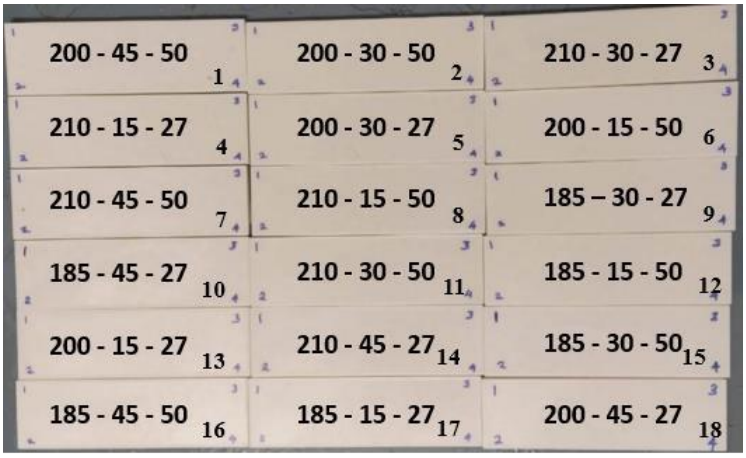

Fig. 2. FDM Fabricated Parts

Table 2. Deviation for Each Combination

S. No	Nozzle Temperature °C	Print Speed mm/s	Bed Temperature °C	Thickness at Edge 1 mm	Thickness at Edge 2 mm	Thickness at Edge 3 mm	Thickness at Edge 4 mm	Average Thickness at Edges mm	Thickness at Center	Deviations
1	200	45	50	4.77	4.7	4.7	4.72	4.7225	4.92	0.1975
2	200	30	50	4.61	4.36	4.62	4.64	4.5575	4.88	0.3225
3	210	30	27	4.6	4.64	4.58	4.58	4.6	4.845	0.245
4	210	15	27	4.75	4.16	4	3.97	4.22	4.95	0.73
5	200	30	27	4.51	3.89	4.28	4.09	4.1925	4.95	0.7575
6	200	15	50	4.78	4.77	4.74	4.75	4.76	4.91	0.15
7	210	45	50	4.62	4.49	4.67	4.69	4.6175	4.86	0.2425
8	200	30	27	4.51	3.89	4.28	4.09	4.1925	4.95	0.7575
9	200	30	50	4.61	4.36	4.62	4.64	4.5575	4.88	0.3225
10	200	30	27	4.51	3.89	4.28	4.09	4.1925	4.95	0.7575
11	210	15	50	4.79	4.7	4.51	4.63	4.6676	4.91	0.2525
12	185	30	27	4.75	4.76	4.05	4.6	4.54	4.866	0.325
13	185	45	27	4.21	3.61	3.97	3.94	3.9325	4.87	0.9375
14	200	30	50	4.61	4.36	4.62	4.64	4.5575	4.88	0.3225
15	200	30	27	4.51	3.89	4.28	4.09	4.1925	4.95	0.7575
16	210	30	50	4.73	4.72	4.73	4.77	4.7375	4.955	0.2175
17	185	15	50	4.68	4.68	4.79	4.71	4.715	4.935	0.22
18	200	15	27	4.69	4.72	4.76	4.78	4.7375	4.88	0.1425
19	200	30	27	4.51	3.89	4.28	4.09	4.1925	4.95	0.7575
20	210	45	27	4.64	4.74	4.72	4.77	4.7175	4.92	0.2025
21	185	30	50	4.72	4.56	4.19	4.24	4.24275	4.87	0.4425
22	200	30	50	4.61	4.36	4.62	4.64	4.5575	4.88	0.3225
23	185	45	50	4.81	4.71	4.27	4	4.4475	4.92	0.4725
24	200	30	50	4.61	4.36	4.62	4.64	4.5575	4.88	0.3225
25	185	15	27	4.74	4.71	4.78	4.77	4.75	4.97	0.22
26	200	45	27	4.75	3.9	4.64	4.59	4.47	4.9	0.43

5 Results and Discussion

Based on the results, the deviation is lowest when the parameters are set to Nozzle temperature: 200°C, Print speed: 15mm/s, and Bed temperature: 27°C. Therefore, the optimal combination of process parameters is Nozzle temperature: 200°C, Print speed: 15mm/s, and Bed temperature: 27°C. The optimal combination of process parameters is displayed in Table 3.

Table 3. Optimal Combination of Process Parameter

Nozzle Temperature °C	Print Speed mm/s	Bed Temperature °C
200	15	27

Directing attention to specimens 1, 2, 3, 4, 5, and 6 as illustrated in Figure 3 produced at a nozzle temperature of 185°C, a noteworthy observation emerges. Among these specimens, the lowest warping deformation (below 5%) is achieved when the printing speed is set at 15mm/s, irrespective of the bed temperature. Notably, elevated printing speeds result in considerable deformation, but this is notably mitigated (below 5%) with a higher bed temperature in place.

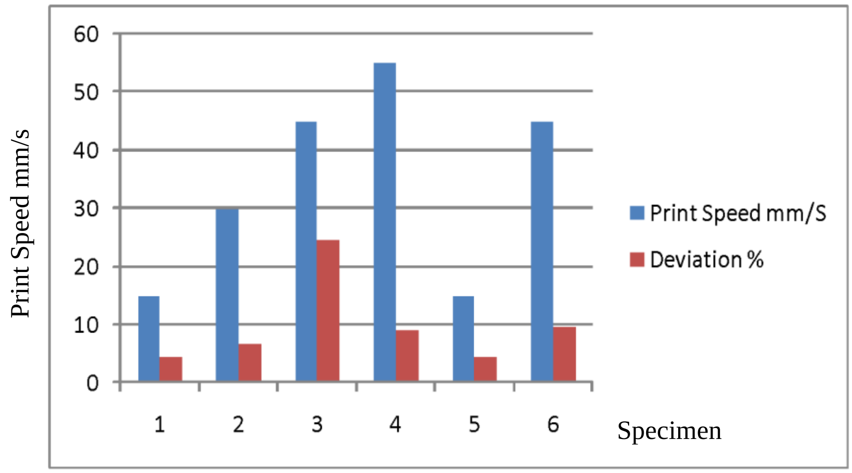

Fig. 3. Effect of Print Speed on Deviation Specimens 1,2,3,4,5 and 6

Examining specimens 7, 8, 9, 10, 11, and 12 as illustrated in Figure 4, which were fabricated with a nozzle temperature of 200°C, reveals a discernible trend. Among these specimens, the most noteworthy observation is that the lowest degree of warping deformation (measuring 2.87%) is achieved when the printing speed is set to 15mm/s, regardless of the bed temperature. However, when employing higher printing speeds, a marked increase in deformation becomes apparent. Nevertheless, this deformation is appreciably mitigated (falling below 5%) when the bed temperature is elevated. Interestingly, a further observation surfaces when comparing the specimens printed at a nozzle temperature of 200°C to those printed at 185°C. Notably, at the higher nozzle temperature of 200°C, the overall deformation is reduced compared to the specimens printed at the lower temperature of 185°C.

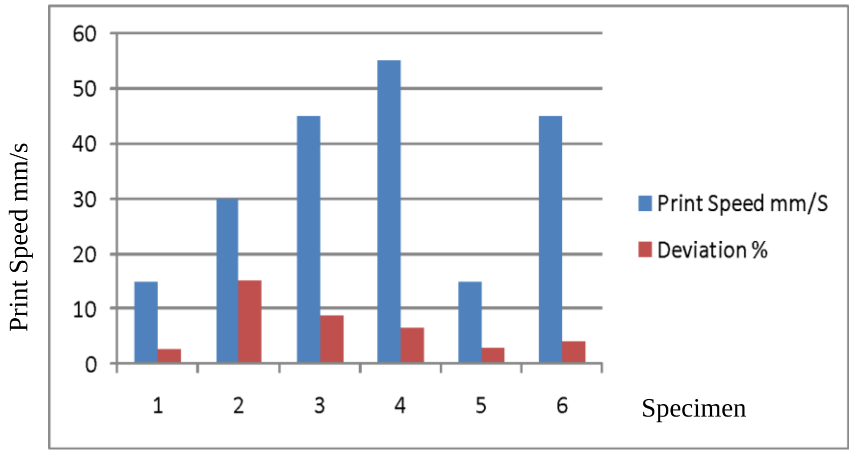

Fig. 4. Effect of Print Speed on Deviation Specimens 7, 8, 9, 10, 11, and 12

Analyzing specimens 13, 14, 15, 16, 17, and 18 as depicted in Figure 5, produced at a nozzle temperature of 210°C, reveals a consistent pattern. Among these specimens, a prevailing observation is that warping deformation consistently remains below 5% when utilizing printing speeds of 30mm/s, 45mm/s, and 55mm/s, regardless of the bed temperature setting. Conversely, when employing a lower printing speed of 15mm/s, a significant degree of deformation becomes evident. However, this deformation is notably mitigated (falling below 5%) when higher bed temperatures are implemented.

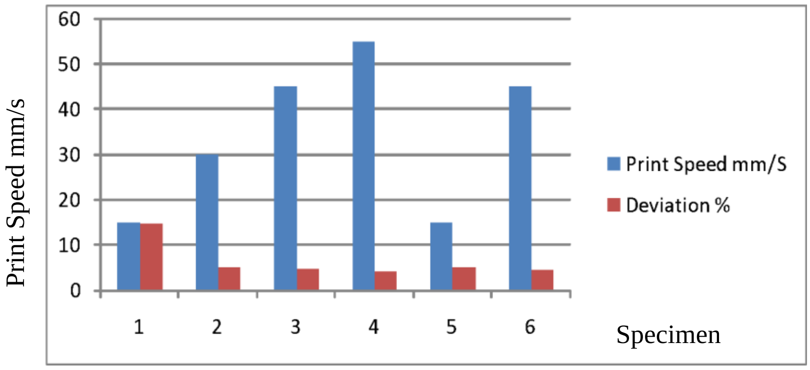

Fig. 5. Effect of Print Speed on Deviation Specimens 13, 14, 15, 16, 17, and 18

To investigate the influence of nozzle temperature on warping while maintaining a constant printing speed of 45mm/s and a bed temperature of 50°C, we selected specimens 6, 12, and 18 as indicated in Figure 6. Notably, elevating the nozzle temperature from 185°C to 200°C resulted in a noteworthy reduction of warping deformation by approximately 50%. However, minimal further enhancement in this regard was observed upon increasing the nozzle temperature to 210°C.

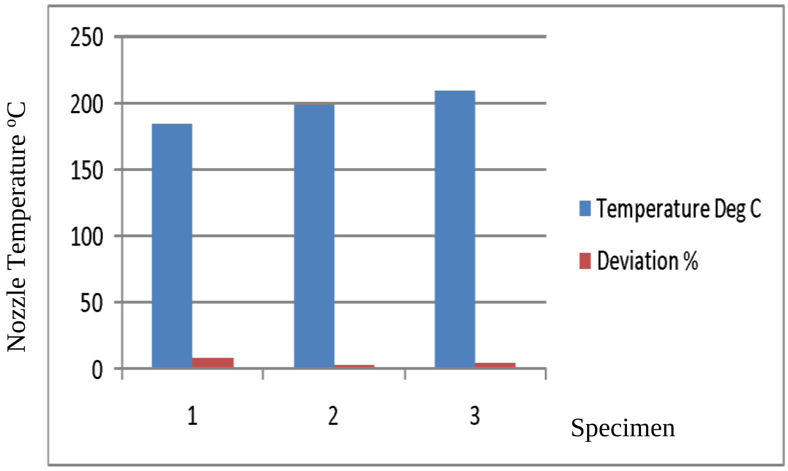

Fig. 6. Effect of Nozzle Temperature on Deviation Specimens 6, 12 and 18

6 Conclusion

Response Surface Methodology (RSM) was employed to optimize process parameters and mitigate warping deformation in 3D printing. The optimal parameters identified for minimizing warping were a nozzle temperature of 200°C, a print speed of 15mm/s, and a bed temperature of 27°C. This combination resulted in significantly reduced warping and improved dimensional accuracy. The optimization of process parameters plays a crucial role in enhancing the quality and reliability of 3D prints. These findings are particularly valuable for users of Creality Ender 3 printers aiming to achieve higher-quality prints with minimized warping issues.

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