A Study on the Influence of Enclosure Temperature Control on the Printing of ABS Filament in a Three-Dimension Printer

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ABSTRACT

Fused Deposition Modeling (FDM) is a newest technique in additive manufacturing, capable of producing complex 3D parts efficiently and cost-effectively without using complicated or expensive dies. One of the most popular materials adopted in 3D printers is the ABS filament, which, despite its high mechanical properties, is susceptible to warping defects which can result in print failures. The objective of this study is to eliminate or minimize the warping defects by installing a temperature control system within the enclosure to prevent rapid cooling during the 3D printing process. The adopted design system uses a thermostat controller, a wire heater, and an enclosure to regulate temperature as required. A series of experimental tests were carried out using a range of sample shapes and sizes at three distinct controlled temperatures (40 °C, 50 °C, and 60 °C). The maximum measured error of 1.463 mm was observed at 40 °C. This variation was attributed to insufficient temperature control and a substantial sample volume of 2,827.44 mm^3. Conversely, the minimum error of 0.223 mm was identified at higher temperatures of 60 °C, with a reduced sample volume of 530.14 mm^3. The study determined that warping, in addition to layer shifting at vertical levels, is a significant contributor to the warping error. The present study recommends the use of an externally controlled temperature in order to enhance the quality and precision of 3D-printed ABS components.

Keywords-Fused Deposition Modeling (FDM); ABS filament; temperature encloser; warping defect

I. INTRODUCTION

Additive manufacturing or 3D printing offers rapid prototyping while reducing development time and costs. It enables customized, complex designs that traditional methods can't achieve. Additionally, it minimizes waste by using only the required material, promoting sustainability [1-3]. The 3D printing technique uses a layer-by-layer construction process, initiated by a Computer-Aided Design (CAD) model. The development of 3D printing technology is remarkably innovative and adaptable. The original materials used in 3D printing were conventional thermoplastics, but now the technology has evolved and encompasses a broad range of materials, including ceramics and metals [4]. Authors in [5] employed a 3D printing process with polymer filament, establishing a foundation for future research focused on the characterization and optimization of Fused Deposition Modeling (FDM) materials and processes. They underscored the significance of many process parameters in determining the quality and mechanical properties of the end product, emphasizing the need for further research.

Authors in [6] investigated the effect of the nozzle diameter on the samples strength and macrostructure and reported that reducing layer heights below standard values leads to enhanced mechanical properties. Authors in [7] revealed the efficacy of 3D printing technologies for rapid prototyping. Using FDM, they demonstrated that diverse, affordable, and non-toxic materials could be used to create functional parts and objects. One of the advantages of 3D printing is the ability to expand the production process to complex shapes while reducing prototype cost, making it valuable and applicable across many fields. Authors in [8] examined the impact of material color on the mechanical properties of components fabricated by FDM. The study studied the impact of eight colors of Polylactic Acid (PLA) and ABS on the compressive, tensile, and flexural strength. Substantial variations in the mechanical properties of the printed products were reported, indicating that filament color significantly influences the FDM performance. For instance, tensile strength measurements revealed a maximum disparity of 36% among different ABS colors. The black samples exhibited the lowest mechanical strength, the red ones the highest tensile and compressive strengths, and the greens the highest flexural strength. It was thus concluded that the influence of material color should not be neglected, particularly when studying the influence of process parameters on the structural performance of FDM parts. Authors in [9] examined the effect of various printing parameters on the compressive strength of ABS materials. The studied parameters included infill densities (25%, 50%, and 75%), infill patterns (trihexagonal, zigzag, and gyroid), and layer thickness (0.1, 0.2, and 0.3 mm). The results indicated that the compressive strength of the printed parts is significantly influenced by these parameters and infill density was identified as the most critical parameter, as determined by the Analysis of Variance (ANOVA). Authors in [10] studied the process parameters of FDM considering the tensile properties of ABS using the Taguchi design of experiments method. The considered printing parameters were layer height, infill density, build speed, and build temperature. The FDM parameters that gave optimum tensile strength were: 45% infill rate, 0.19 mm layer height, 240 °C build temperature, and 180 mm/min build speed. These conditions resulted in a maximum Ultimate Tensile Strength (UTS) value of 39.094 MPa and a minimum tensile strength of 21.945 MPa.

Many filament materials are used in FDM 3D printing, such as ABS, PLA, and PTG. ABS is a thermoplastic copolymer composed of three structural units which provide a balanced set of properties and is considered an excellent base material for a wide range of applications in different industries [11, 12]. Several studies explored the properties of ABS filament, but only a few addressed the challenges associated with 3D ABS printing. One of the most important problems encountered is the warping defect that occurs during the printing process. This defect primarily affects the edges of the printed parts, causing them to rise and form an arc-like shape along the print bed, because the upper layers cool faster than the base layers.

This study examines the challenges associated with printing ABS filament, particularly the issue of warping defects, which can result in print failures and the subsequent dislocation of the 3D-printed components from the printing bed. Specifically, it examines the role of ambient temperature on all the sides of the printer and its effect on minimizing warping, with the aim of optimizing the printing process to improve the quality of the printed part [13]. The investigation into warping defects involves an analysis of the relationship between environmental temperature and the behavior of ABS filament during the printing process. The concept of temperature control during printing has been realized through the implementation of a specialized system comprising a thermostat controller, a heater integrated within an enclosure, and sensors. The efficacy of the method was gauged by the measurement of integrity error in the printed surface, using a high-resolution dial gauge measuring device affixed to a rigid handle apparatus.

II. EXPERIMENTAL WORK

The samples were produced using an Anycubic Mega S FDM printer, which is equipped with a diameter nozzle of 0.4 mm, as shown in Figure 1. The comprehensive technical specifications of the FDM printer configuration are presented in Table I. ABS filament was used.

III. THE ENCLOSER

The enclosure is a box-shaped structure with an acrylic door, measuring 60 × 60 × 60. It is composed of 5-mm-thick wooden pieces and an acrylic door 2.5 mm thick. It features a door handle and a handle at the top to facilitate handling. The enclosure serves to prevent the entry of air currents and to trap the vapors and gases resulting from printing, including toxic gases, as seen Figure 2.

IV. THERMOSTAT STC 3008

The thermostat is a device that controls the temperature. It consists of a microcontroller that regulates the heat with a sensor that detects the temperature. This allows the thermostat to maintain the desired temperature. Figure 3 portrays the STC3008 thermostat, and Table II provides a detailed list of its characteristics. Figure 4 presents the schematic wiring diagram of the thermostat. The subsequent step involves integrating the thermostat with a halogen heater within the enclosure to regulate the temperature of the printing environment as desired.

Fig. 1. Anycubic mega S FDM printer.

TABLE I. ANYCUBIC MEGA S FDM SETUP'S SPECIFICATIONS.

Specification	Details
Resolution of Layer	0.05-0.3 mm
Accuracy of Positioning	*X*/*Y* 0.0125 mm, *Z* 0.002 mm
Travel velocity	150 mm/s
Print velocity	20~100 mm/s (recommended speed 60%)
Supported Print Materials	PLA, Wood, HIPS, ABS
Operational Extruder Temperature	Max 260°C
Diameter of Nozzle	0.4 mm/1.75 mm
Build Size	210 × 210 × 205 (mm)
Input Formats	. STL, DAE, AMF, OBJ
Ambient Operating Temperature	8 °C – 40 °C
Slicer Software	Cura

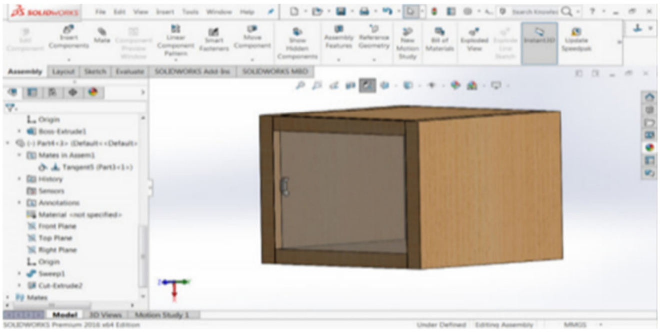

Fig. 2. The encloser.

V. THE ADOPTED SAMPLES WITH PRINTING PARAMETERS

The experiments were designed using the Taguchi approach, a powerful design approach aimed at optimizing quality and performance with a minimal number of experiments. To examine the impact of the encloser temperature on the printing process of the ABS filament, a series of cylindrical samples with varied dimensions, including shape, volume, and surface area, were selected for investigation. The specific dimensions of the cylindrical samples are outlined as: diameter (10 mm, 15 mm, 20mm) and height (3 mm, 6 mm, 9mm).

Fig. 3. Thermostat controller unit.

TABLE II. THERMOSTAT SPECIFICATIONS

Specification	Details
Product name	Microcomputer temperature controller
Product number	STC-3008
Supply voltage	12 V, 24 V, or 110-220 AC
Temperature range	-55 °C ~ +120 °C
Temperature measurement accuracy	±1 °C
Line length	1 m
Size	75 mm × 85 mm × 35 mm

The objective was to analyze the influence of various enclosure temperatures (40 °C, 50 °C, and 60 °C) on the warping and layer-shifting defects that occurred in the ABS 3D-printed parts. This systematic approach facilitated the comprehension of the interplay between temperature and geometry on print quality with ABS filament. Figure 5 shows the cylindrical samples sliced with the CURA slicer. In this study, the selected parameters were presented as enclosure temperature, surface area, and sample volume. The ensuing table provides a comprehensive overview of the selected parameters, as derived from the Taguchi design. The three fundamental parameters that were selected for the experimental thesis are encloser temperature, surface area, and volume. Table III provides a comprehensive overview of the experimental parameters employed for the cylindrical sample. Subsequent to the aforementioned steps, the ensuing stage entails the placement of the 3D printer within the enclosure, as displayed in Figure 6.

The printing process is initiated, resulting in the production of the designated samples according to specific parameters selected based on various considerations. These parameters are maintained constant for all samples to ensure uniformity. However, variations occur in the shape, volume, and size of the samples. The rationale behind this selection is to measure the warping defects in the different surface areas with varying thicknesses in the adopted samples, while fixing all other printing parameters. These parameters are selected through the adoption of the Taguchi design. The experimental design included nine samples, which are demonstrated in Figure 7.

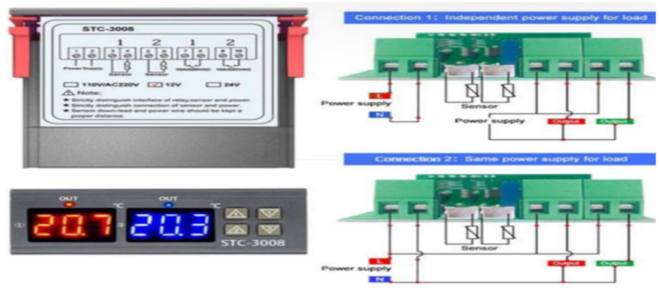

Fig. 4. Schematic wiring of thermostat.

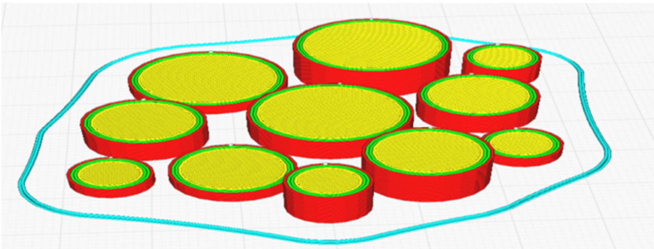

Fig. 5. The cylindrical samples sliced in CURA Slicer software.

TABLE III. THE ADOPTED EXPERIMENTAL PARAMETERS FOR CYLINDRICAL SAMPLES

Encloser temp.	Diameter mm	High mm	surface area mm^2	Volume mm^3
40	10	3	78.53	235.61
40	15	6	176.71	1,060.28
40	20	9	314.15	2,827.44
50	10	6	78.53	471.23
50	15	9	176.71	1,590.43
50	20	3	314.15	942.47
60	10	9	78.53	706.85
60	15	3	176.71	530.14
60	20	6	314.15	1,884.95

(a)

(b)

Fig. 6. (a) Heat fixed inside the encloser, (b) 3D printer inside the encloser.

Fig. 7. Printed cylindrical samples.

VI. WARPING MEASUREMENT TEST

A study was conducted to examine the effects of heat on the 3D printer parts. Nine samples of varying shapes and dimensions were exposed to three distinct temperatures to assess the impact of environmental temperature on the 3D-printed ABS filament parts. The objective of this study was to investigate the influence of heat on the occurrence of wrapping defects and to determine effective methods for their elimination or minimization.

VII. THE ADOPTED MEASUREMENT WARPING DEVICE

The measurement of the warping defect was executed by employing a high-precision digital dial gauge, which was mounted on a robust stand. This configuration was selected for the measurement process. Table IV presents the specifications of the digital dial gauge that was adopted for these measurements.

As shown in Figure 8, the warping measurement device is affixed to the 3D printer, and the warping error on the cylindrical sample is measured.

TABLE IV. DIGITAL DIAL GAUGE BRAND SYNTAX

Model Number:	**0-12.7 mm**
Resolution:	0.001 mm
Max Measuring Range:	11- 29 mm
DIY Supplies:	Woodworking
Display Type:	Digital
Dial Indicator Style:	Vertical

(a)

(b)

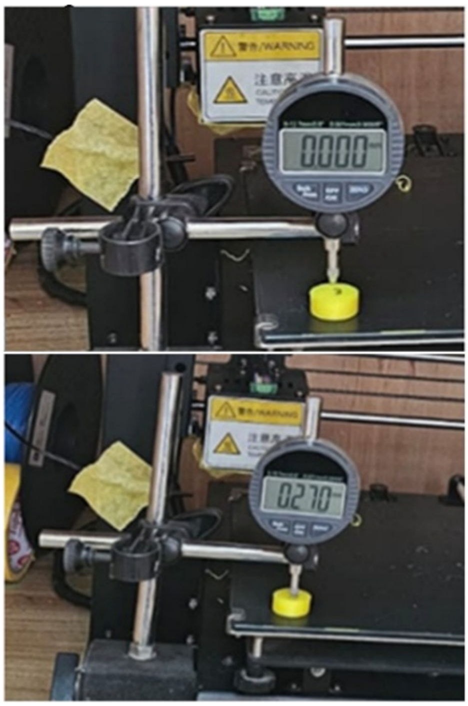

Fig. 8. Measure warping error: (a) set the device to zero, (b) measure the maximum error on sample 1.

VIII. RESULTS

The experimental data have been measured and recorded and the data from the warping test for four samples have been registered, while the warping error is presented in Table V.

As depicted in Table V, the sample with the highest error rate was identified as sample 3, with a recorded value of 1.463 mm. The primary contributing factors to this elevated error rate were attributed to the low enclosure temperature of 40 °C and the sample's substantial surface area of 314.15 mm^2 and volume of 2827.44 mm^3. In contrast, sample 8 exhibited the lowest error rate. The observed minimum error can be attributed to the rise in temperature and the reduced surface area 176.71 mm^2 and volume 530.14 mm^3 of sample 8. Figure 9 presents the primary effect of the warping error on the range of enclosed temperatures, surface areas, and volumes of nine cylindrical samples. The oscillation of volumes is indicated, with numerous points being evident on the curve. This is due to the variation in volumes among the samples. The surface area and enclosure temperature are constrained by three values, as indicated by the three points. In addition, Figure 9 provides further insight into the relationship between the temperature and warping error in 3D printing. The results demonstrated the impact of temperature and sample size on the quality of 3D printing. The findings indicated that increasing the temperature led to a reduction in wrapping. Additionally, it was observed that enhancing the sample size, particularly its thickness, resulted in an increase in the warping error.

TABLE V. MEASURED WARPING ERROR FOR CYLINDRICAL SAMPLES

Encloser temp. °C	Diameter (mm)	High (mm)	Surface area (mm^2)	Volume (mm^3)	Warping defect (mm)
40	10	3	78.53	235.61	0.641
40	15	6	176.71	1,060.28	0.896
40	20	9	314.15	2,827.44	1.463
50	10	6	78.53	471.23	0.660
50	15	9	176.71	1,590.43	0.499
50	20	3	314.15	942.47	0.573
60	10	9	78.53	706.85	0.386
60	15	3	176.71	530.14	0.223
60	20	6	314.15	1,884.95	0.270

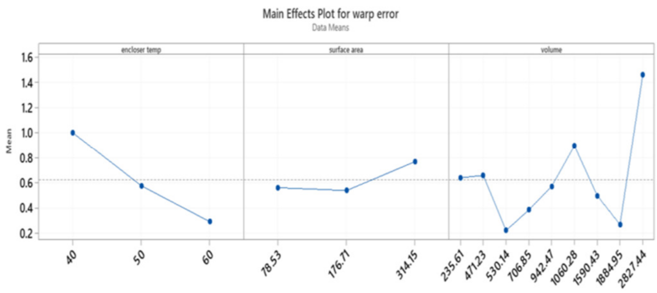

Fig. 9. The main effect of warping error with the range of enclosed temperature, surface aera, and volume of nine cylindrical samples.

IX. CONCLUSIONS

The most significant conclusions that were derived from this study are summarized as:

- The study identified a maximum measured error of 1.463 mm, which occurred at 40 °C. This discrepancy was attributed to inadequate temperature control and a substantial sample volume of 2,827.44 mm³. Conversely, the other samples exhibited an error lower than that of sample 3 at the same temperature. This was attributable to the high thickness or volume of sample 3 compared to the other samples, as showcased in Figure 9.
- It was observed that the minimum error attained a value of 0. 223 mm. This error minimization can be attributed to the elevated environmental temperature (60 °C) within the enclosure. Conversely, the other samples exhibited higher errors compared to sample 8 at the same temperature. This discrepancy can be attributed to the reduced thickness or volume of sample 8, despite its comparatively large surface area when contrasted with the other samples.
- The significant conclusion of this study is that warping is not the sole cause of the defects in Acrylonitrile Butadiene Styrene (ABS) 3D printing, but layer shifting in vertical planes also plays a substantial role.
- As observed in sample 3, augmenting the height resulted in layer shifting and an escalation in the error across numerous vertical levels.

Future advancements in 3D printing are anticipated to encompass faster printing speeds and enhanced precision, enabling the fabrication of more intricate designs. Advancements in material science will facilitate the usage of stronger, more versatile materials, including biomaterials. Furthermore, the integration of artificial intelligence and automation is poised to streamline processes, enhancing customization and scalability in manufacturing. To this end, researchers in the field of 3D printing should prioritize fostering interdisciplinary collaborations, with the aim of bridging the gaps between material science, engineering, and ethics. The promotion of open-source research and data-sharing can enhance transparency and reproducibility. Incorporating diverse perspectives and addressing sustainability concerns will help ensure inclusive and responsible advancements in the field.

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