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Shrinkage Compensation for FFF Printing for PLA, ABS, and PETG Thermoplastics

Ariel Weiser, Brandon Kipp, Matthew Dillon, Shawn Ralph, Kyle Rodriguez, Andrew Young, Deshaboina Saikumar, and Christopher Greene

Binghamton University
Department of Industrial and Systems Engineering
Binghamton, NY

Corresponding author's Email: aweiser2@binghamton.edu

Author Note: Ariel Y Weiser, Brandon Kipp, Matthew Dillon, Shawn Ralph, Kyle Rodriguez, Andrew Young, and Deshaboina Saikumar are students at Binghamton University's Thomas J. Watson School of Engineering. Dr. Christopher M Greene, Assistant Professor in the Department of Systems Science and Industrial Engineering, is the Capstone group's advisor. Correspondence concerning this paper should be addressed to Ariel Y Weiser, Department of Industrial and Systems Engineering, Binghamton University, 4400 Vestal Parkway East, Binghamton, NY 13902. E-mail: aweiser2@binghamton.edu

Abstract: Company X assembles printed circuit boards (PCBs) that have components requiring protection from external factors. A conformal coating process adequately protects these parts, while parts not requiring protection are shielded from the process. Company X employs the use of Additive Manufacturing technologies to print custom covers for the circuit board parts needing protection from the conformal coating process. There exists a high defect rate among various thermoplastics used in 3D printing processes, as the materials expand and contract at varying rates. This high defect rate is due in part to warpage and deformation in printed parts. The purpose of the research presented in this article is to compensate for warpage and deformation of parts printed from PLA, ABS, and PETG filaments utilizing optimal print parameters. Results were obtained by printing sample 3D models with the QIDI X-One2 Fused Deposition Modeling (FDM) printer and examining dimensional accuracy.

Keywords: 3D Printing, Thermoplastics, Expansion, Contraction

1. Introduction

To protect its Printed Wiring Boards (PWBs), Company X utilizes a conformal coating process. Though the coating exists to protect certain components from external factors, there are other components that may be damaged by the process. Company X employs the use of 3D printing to produce covers for these components to shield them from the conformal coating process. Though 3D printing is superior to a taping technique previously used, the printed parts expand and contract at varying rates based upon the thermoplastic and shape of the part. There exists a high defect rate in the printed covers due to the size changes and low dimensional tolerance of circuit boards.

FDM is an Additive Manufacturing process used in the creation of the circuit board covers and entails a roll of plastic filament to be heated through a nozzle, then extruded onto a build platform. The shape of the print and its infills are printed layer by layer until the object is complete.

Research by Dey et. al (2019) examined the relationship between print parameters and the dimensional accuracy of printed parts. After conducting a meta-analysis of over one hundred research papers on the topic, multiple conclusions were drawn regarding optimal parameters for printing. For instance, it was discovered that six print parameters significantly affect the dimensional accuracy of FDM printed parts. These parameters include layer thickness; air gap; build orientation; raster width; raster orientation; print speed; and extrusion temperature. Additionally, it was concluded that the highest dimensional accuracy for printed parts was achieved through setting a low layer thickness, low number of shells, and low extrusion temperature.

Upon reviewing the literature surrounding the topic of dimensional accuracy for FDM printed parts, it was determined that optimizing print settings produces higher quality prints. Printed parts with higher dimensional accuracy reduce the need to reprint part covers whose deformation exceeds acceptable tolerance levels for circuit boards. By reducing the need for reprints, both the time devoted to printing and the costs associated with the process will be minimized.

2. Literature Review

To expand the foundation of knowledge regarding 3D printing, a literature review was conducted to examine the current body of knowledge surrounding the topic of thermal expansion in 3D printed models. Specifically, emphasis was placed on understanding how various print parameters might affect the structural integrity of 3D printed parts. By understanding the relationship between print parameters and structural integrity, a prediction of the degree to which part expansion occurs can be formulated.

D'Amico et al. (2017) studied the relationship between layer thickness and part deformation in FDM 3D printed parts. Part deformation was induced by annealing 3D models made with ABS above their respective glass transition temperature, T_g. D'Amico et al. observed greater deformation occurring within parts of smaller layer thickness as the increased number of layers allowed greater build up of residual stress compared to parts of higher layer thickness with reduced numbers of layers. The relationship between irreversible thermal strain and decreasing layer thickness was cited as being up to a 22% greater strain.

Wu et al. (2016) studied the effects of isotropic negative thermal expansion metamaterials. They found that two and three dimensional artificial materials with negative thermal expansion properties had large and tailorable CTEs or coefficients of thermal expansion. They proposed a novel method to achieve two and three dimensional negative thermal expansion via anti-chiral structures. The two-dimensional metamaterial is constructed with unit cells that combine bimaterial strips and anti-chiral structures, while the three dimensional metamaterial is fabricated by a multi material 3D printing process. The mechanism proposed here is theoretically scale independent, meaning that the concept of manipulation of thermal expansion could be extended to the micro or nanoscale if appropriate component materials and fabrication processes are available.

Kantaros et al. (2013) studied the magnitude of the solidification induced residual strains in FDM fabricated parts using different processing parameters with two big parameters considered, layer thickness and deposition orientation. It was found that the residual strain in the 0 direction, where the roads were aligned with the long dimensions of the printed object, were consistently lower than the transverse, 90 degree and criss-cross 45 degree directions with a .25mm layer thickness. However, when thickness was increased to .5mm, the measured strains of the 0 and 90 degree were comparable. The thermal cycling analysis showed that the CTE of the FBG reading were in good agreement with those reported in their literature.

Weng et al. (2016) studied the mechanical and thermal properties of ABS, or Acrylonitrile butadiene styrene, and montmorillonite nanocomposites for fused deposition model 3-D printing. It was found that the addition of OMMT in different amounts significantly increased the tensile modulus, flexural strength, flexural modulus and dynamic mechanical storage modulus, and decreased the linear thermal expansion ratio and the weight loss of TGA. The addition of OMMT increases the mechanical properties of printed samples more than samples prepared with injection molding.

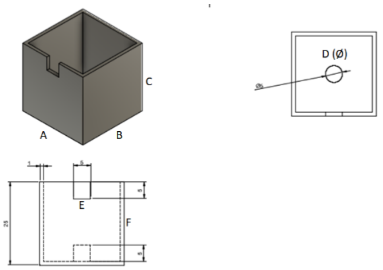
3. Method

3.1 Data Collection

Previous findings suggest that there exist differences in expansion rates between several types of thermoplastics that Company X uses for part coverings. To examine this hypothesis, prints were created using models obtained by the team. Three different part models were printed using three different filaments, ABS, PLA, and PETG. Three samples of each individual part combination were then printed for a total of 27 printed parts. Each part was then measured by a group of three team members, each of whom used a Neiko 01407A Electronic Digital Caliper to collect the axial dimensions. The measurement process was conducted twice on each part to ensure accuracy.

3.2 Design

The team obtained models of printed covering board parts, detailing each dimension of the part to be printed. One of the designs is shown in Figure 1, with the 3D-printed model shown in Figure 2:



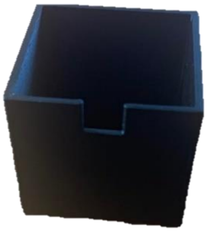


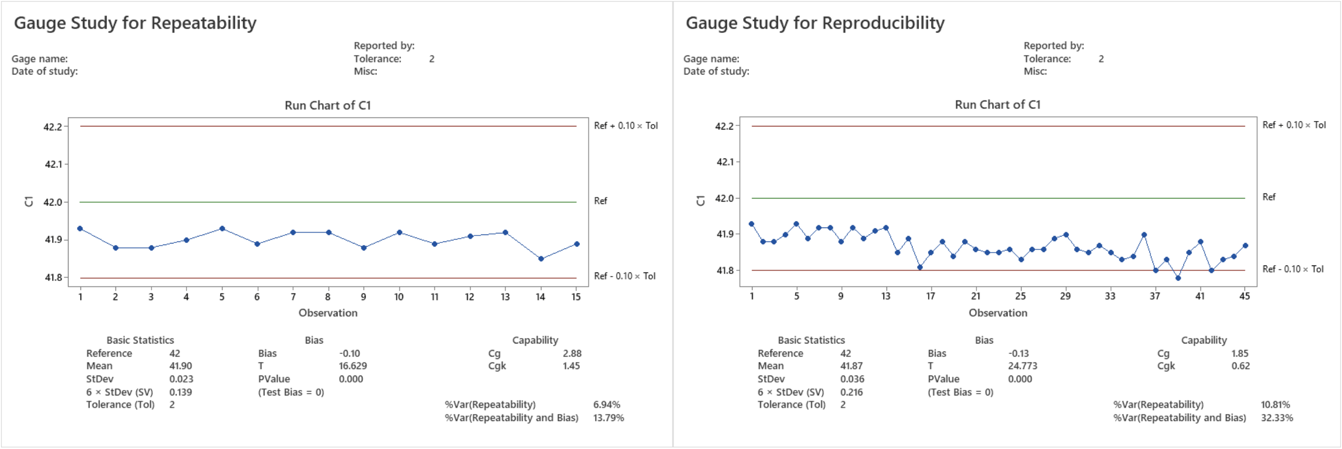
Figure 1. New Design Detailed Drawing

Figure 2. New Model Print

The aforementioned drawings were each printed three times, followed by another set of three samples using each of the three filament types: ABS, PETG, and PLA.

3.3 Gauge Repeatability and Reproducibility Study

The project also conducted a Gauge Reproducibility study. This study explored the P/T ratio of the designs which refers to the relationship between precision and tolerance. The results are shown in Figure 3. Reproducibility in our design has a P/T ratio of 0.108. A ratio of below 0.1 is ideal and below 0.3 is acceptable. This confirms our reproducibility has a high degree of precision. Repeatability has a ratio of .0694 this is below the ideal ratio of .1. This means that our process used for measuring the parts is very precise.



Gauge Study for Repeatability

Gage name:
Date of study:
Reported by:
Tolerance: 2
Misc:

Basic Statistics		Bias		Capability	
Reference	42	Bias	-0.10	Cg	2.88
Mean	41.90	T	16.629	Cgk	1.45
StDev	0.023	PValue	0.000		
6 × StDev (SV)	0.139	(Test Bias = 0)			
Tolerance (Tol)	2			%Var(Repeatability)	6.94%
				%Var(Repeatability and Bias)	13.79%

Gauge Study for Reproducibility

Gage name:
Date of study:
Reported by:
Tolerance: 2
Misc:

Basic Statistics		Bias		Capability	
Reference	42	Bias	-0.13	Cg	1.85
Mean	41.87	T	24.773	Cgk	0.62
StDev	0.036	PValue	0.000		
6 × StDev (SV)	0.216	(Test Bias = 0)			
Tolerance (Tol)	2			%Var(Repeatability)	10.81%
				%Var(Repeatability and Bias)	32.33%

Figure 3. Gauge R&R Study

4. Results

Our research was an expansion on an existing study of 3D printed parts. A comprehensive analysis was conducted to formulate an initial understanding of the problem at hand. An initial sample of 90 prints, divided amongst three thermoplastics, were produced for each 3D model obtained by the team. The parts were then observed for expansion and shrinkage. The findings were then visualized by a linear regression model. (Antonacci, 2020)

4.1 Analysis of Part Expansion

Table 1. Average Shrinkage

	X	Y	Z
ABS	0.005899333333	0.006921516667	-0.009244133333
PETG	0.00755079	0.005372313333	0.007302333333
PLA	0.006312726667	0.003500823333	0.0080002

Table 2. Transformation Formula Based on Average Shrinkage

	X	Y	Z
ABS	1.005934342	1.006969758	0.990840538
PETG	1.007608238	1.005401331	1.00735605
PLA	1.00635283	1.003513122	1.008064719
Formula Calculation = 1/(1-Average Shrinkage)			

The average amounts that the 3D printed parts shrank for each axis and material was calculated. These values were then used to calculate an expansion coefficient for each axis and part combination. These values will be used to adjust the models to make future prints more accurate.

4.2 Linear Regression

We compared our approach to a linear model proposed in a previous study (Antonacci, 2020), shown in Table 3. The Y-axis follows a linear regression with values ranging from 77.25% to 93.18% with values changing based on the material type used. The other axes only follows a general linear regression pattern, but the P-values are all still over 0.05. This indicates that the axis still follows a linear trend but because the correlation is not high it is not a strong predictor. The team analyzed the linear regression model previously developed, and noted which axes expanded and contracted based on the different thermoplastics observed. To further expand their foundation of 3D printing knowledge, the team completed an extensive literature review on various Additive Manufacturing techniques, specifically Fused Deposition Modeling/Fused Filament Fabrication. Research into the three thermoplastics used—ABS, PLA, and PETG—was also completed. The team then reproduced the work of the existing study, reprinting and measuring parts to measure shrinkage and expansion. A Gauge R&R study was then conducted on the reprinted parts to ensure that the results matched those previously obtained. The team concluded that the parts could be printed using the same setting as the existing study due to the high degree of normality and small spread of part variation. This means that the existing settings are a usable basis because the printer and setting give results that are similar to the existing study (Antonacci, 2020).

Table 3. Summary of Results of Linear Regression Analysis

Material	Axis	S	R-Sq	R-Sq (Pred)	P Value
ABS	X	0.0064660	39.62%	0.00%	0.567
	Y	0.0038476	77.25%	0.00%	0.317
	Z	0.0069967	68.72%	0.00%	0.378
PLA	X	0.0064241	37.50%	0.00%	0.580
	Y	0.0005068	92.66%	0.00%	0.175
	Z	0.0119339	4.81%	0.00%	0.859
PETG	X	0.0081828	36.84%	0.00%	0.58
	Y	0.0019864	93.18%	0.00%	0.168
	Z	0.0084643	4.72%	0.00%	0.861

The team analyzed the data from the existing study to create a mathematical model to predict the expansion and shrinkage of the 3D printed parts. The team will then apply those adjustments to a new set of printed parts and analyze if the adjustment did in fact correct the shrinkage and expansion.

5. Interpretation of Results

Analysis of the reprinted test samples by axis found that normality was established for two out of three part models. Of the parts printed, a third model did prove to inconsistently achieve normality dependent upon the axis measured. This particular model only achieved normality when measured across its X-axis. Given the large size of the model, however, its build plate orientation was altered so as to make a successful print possible. In doing so, the build orientation of this model was orthogonal, at a 45-degree angle, across the build plate compared with that of the other two part models' 0-degree orientation. Research conducted in the team's literature review has confirmed that such a compromise is significant and that a deviation from the 0-degree orientation would negatively affect part integrity. As such, further research is needed to confirm the dimensional accuracy of this third model when aligned at a 0-degree build orientation as was done with the two previous part models.

6. Discussion

Research on the fundamentals of 3D printing was conducted in order to establish a basis of knowledge for the project. An analysis of the existing study project team was imperative to developing a proper project definition and understanding. Thermal expansion was determined to occur in samples of the 3D printed parts─an outcome the existing study team had not accounted for. This knowledge was then applied in order to modify the project definition and desired outcomes.

Following the establishment of the problem definition, a method by which to solve the problem was designed. A set of test parts was made to establish that the current printer was capable of reproducing the printed parts. Test parts were printed based on specifications obtained and the existing study in order to ensure printability (Antonacci, 2020). This limited the number of variables and gave the test parts the greatest chance of being printed accurately. Once the test prints were measured and found to meet the required standard, a set of parts with adjusted measurements could be printed. The adjustments are based on the average expansion and contraction from each axis and material combination. For example, the Y-axis numbers for each part made of ABS was averaged over all parts to find an average Y-axis ABS expansion or contraction rate. These numbers are based on the part information from the existing study. This method was then used to create an expansion ratio for each axis and material. The original models were then altered to reflect the needed resizing. These parts will be printed, and a Gauge R&R performed to find if this resizing method prints parts that are more consistently accurate for the needed dimensions of the part covers.

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