PROCESS MODELING OF THERMOPLASTICS AND THERMOSETTING
POLYMER MATRIX COMPOSITES (PMCs) MANUFACTURED USING FUSED
DEPOSITION MODELING (FDM)

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ABSTRACT

PROCESS MODELING OF THERMOPLASTICS AND THERMOSETTING POLYMER MATRIX COMPOSITES (PMCs) MANUFACTURED USING FUSED DEPOSITION MODELING (FDM)

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In this work, a model framework for the simulation of Fused Deposition Modeling (FDM) of thermoplastic and thermosetting polymers and Polymer Matrix Composites (PMCs) was developed. A Python script was constructed to automatically generate a 3D finite element heat transfer and stress model of individual roads within a 3D printed part. The script creates the road activation sequence based on the print path specified in the part G-code and associated boundary conditions which are continuously updated throughout the analysis with minimal input from the user. Thermosetting polymers and polymer matrix composites (PMCs) are modeled by implementing a material sub-model from Convergent Manufacturing Technologies called COMPRO that captures the curing kinetics of the material during the printing and post-cure cycle. The modeling approach is formulated for both material systems through tailorable conditions such as build plate temperature, ambient conditions, print temperature, etc. To the author’s knowledge, no 3D finite element model of the FDM process exists for the thermal history and residual stress prediction of
thermosetting polymers and PMCs.

Although the objective of this work is to create a model for the prediction of thermosetting polymers and PMCs, the characterization and subsequent printing of these materials is still in the development stages. Therefore, in order to validate that the proposed model is capturing the correct physics for the FDM process, model predictions for Acrylonitrile Butadiene Styrene (ABS) coupons were compared with experimentally printed specimens. A series of sensitivity studies were then performed for this model to investigate significant effects as well as trends in the predictions from assumptions in the boundary conditions. The model is then extended to thermosetting PMCs to demonstrate the linkage between COMPRO and the modeling framework.
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CHAPTER 1
INTRODUCTION

1.1 Previous Efforts in Modeling/Predicting

Additive manufacturing (AM) is described as the process of creating parts layer-by-layer, enabling the creation of complex geometries otherwise unattainable using traditional subtractive manufacturing methods. Fused Deposition Modeling (FDM) is one of the most widely used AM techniques in which solid filament is melted and extruded through a heated nozzle and deposited onto a substrate or previously extruded roads. A well-documented drawback with FDM processes is the need for process optimization that often requires tedious trial-and-error experimentation of the hardware, software, and material properties to affect the end quality of the part [1, 2]. Process modeling can be used to reduce this inefficient method for existing materials and also aid in the exploration of optimal print parameters for new feedstock materials, such as thermosetting polymers.

Modeling of additive systems is complex due to the constantly evolving geometry and complex viscoelastic nature of the material during the printing process. Many research studies focus on varying the printing parameters (e.g. print speed, build temperature, raster angle, etc.) to improve mechanical properties and dimensional accuracy in thermoplastic parts [3-6]. Other efforts have focused on different physical and thermal aspects of the FDM process such as the liquefier dynamics, die swelling, or deposition and bonding [7]. Given the complex thermal history (i.e. cooling, local reheating) much research has focused
on this phenomenon to estimate the road-to-road adhesion, residual stress, and deformation in 3D printed parts. Since the neck growth, or degree of bonding between roads indicates the effectiveness of the mechanical properties, much research as focused on this aspect of additive manufacturing. Reducing the problem to a 1D lumped capacity sintering model, the potential degree of bonding and necking between roads in which a direct comparison between this model and the manufacturing parameters was investigated to determine the influence on the neck growth [8]. The study determined that the extrusion temperature had the most significant impact on the neck growth. This was later verified in a separate modeling and experimental study [9]. Two-dimensional heat transfer models have also been implemented to characterize the thermal behavior within single and multiple roads. The bond strength between roads was evaluated in a 2D analysis in order to predict the mechanical properties of additive parts [10]. In a comparative study of the neck growth with experimental data, it was determined that the proposed 2D analysis showed better agreement with the data at low temperatures while the 1D model performed better at higher temperatures, further verifying the complex thermal nature of the process [11]. Other efforts have also used a 2D modeling approach while incorporating a crystallinity model for the material throughout the printing process. These crystalline regions can affect both thermal and mechanical properties such as thermo-elastic shrinkage or contraction in a printed part [12]. Studies have also evaluated different aspects of the complex thermal phenomena which occur during the printing process (e.g. radiation and conduction between roads, convection with entrapped air in voids, convection and radiation with environment, etc.) in order to determine which aspect was the most impactful [13].

Thermo-mechanical models that incorporate the thermal effects and subsequent
residual stresses throughout the printing process have also been evaluated. One of the first 3D thermo-mechanical finite element models to demonstrate an additive process simulated the deposition process by activating just 16 brick elements in a predetermined path [14]. Additional efforts have adopted this element activation approach in order to simulate the 3D printing of Acrylonitrile Butadiene Styrene (ABS) while optimizing the print parameters to minimize residuals stress and deformation [15, 16]. FDM parts have shifted toward structural end-use parts by incorporating reinforcement materials into ABS and higher-grade resins [17- 20]. This method has also been implemented in commercial software by combining multi-scale mechanics with FEA and damage prediction for the printing of neat and carbon fiber reinforced thermoplastic parts [21].

1.2 Thermosetting Materials

Continuous research in fused deposition modeling has also been focused on advanced filament material development. For polymeric systems, materials with high modulus for high temperature applications while maintaining printability are desired for many fields. Thermosetting polymers are an obvious choice for advanced additive manufacturing due to their mechanical properties and thermo-oxidative stability at high service temperatures [22, 23]. A study showed much success in 3D printing a thermosetting epoxy ink. The material, which included a low volume percent of chopped carbon fibers, was extruded at room temperature using clay as a shear thinning rheological modifier to hold the extruded shape before being thermally cured. Mechanical testing of this formulation showed higher modulus and strength values when compared to the base epoxy ink [20]. Combining traditional high grade composite technology with additive manufacturing would further extend the technique to aerospace and defense applications.
Additive systems exemplify significant potential in repair applications for complex and unique structures due to the flexibility in material, part geometry, cost, and lead time. Additive systems are ideal for unique or low-volume parts for aircraft since forming dies or legacy part replacement can cost thousands of dollars [24].

1.3 Proposed Model

The research presented in this thesis builds on these previous efforts by creating a 3D finite element thermo-mechanical model for additively manufactured thermoplastic and thermosetting polymers. The model features a transient heat transfer analysis driven by convection with the environment as opposed to a defined temperature definition following the print path. Additionally, the model is coupled with a material sub-model to capture the curing kinetics for the thermosetting polymer material. A Python script was developed to automate the model creation process which includes continuously updated convection surfaces for the evolving volumetric changes during the printing process.

The ultimate goal for this work is to create a model for predicting the thermal history, residual stress, and deformation in additively manufactured thermosetting materials. Since these materials are still in the development stages and not commercially used in AM, the model framework was first calibrated for Acrylonitrile Butadiene Styrene (ABS), a commonly used thermoplastic filament material. The model predictions for the ABS material were then compared to experimentally printed samples for validation that the model is capturing the correct physics. The model is then extended to thermosetting polymers and polymer matrix composites (PMCs) to demonstrate the linkage between the complex finite element model and cure kinetics material model.

In this work, methodology using a Python script for the model generation, along
with the general boundary conditions, are first introduced. The experimental methods used to calibrate the thermoplastic (ABS) model are described, followed by an overview of the boundary conditions and assumptions specific to this material. These initial conditions and assumptions for the thermoplastic model are referred to as the baseline model. The baseline model predictions are followed by a series of sensitivity studies where certain assumptions are varied and the outcome (i.e. deflection) is recorded. The general model framework is then applied to a thermosetting polymer and polymer matrix composite (PMC) system. The thermosetting model predictions are then discussed, followed by concluding remarks and areas for future work and model development.
CHAPTER 2
METHODOLOGY

The finite element model to simulate the 3D printing process uses a Python script to automate the tedious task of creating a finite element model for a sequential heat transfer and stress analysis. The model geometry, individual road activations, and continually-changing boundary conditions associated with the heat transfer and stress analyses are automatically generated by running the Python script within Abaqus, with minimal input from the user. The general framework of the model also allows for easy modification of the boundary conditions or materials used in the analysis.

2.1 Model Setup and Python code

Like the additive manufacturing process itself, the analysis starts with a 3D CAD model of the geometry. The 3D CAD model is processed using a 2D slicing program, discretizing the 3D model into 2D drawings to describe the print path for model creation. This information along with other printing parameters such as feed rate, scanning speed, platform and extrude temperatures are compiled into a G-code, which is the input file used by the 3D printer. A Matlab code was developed to extract the spatial coordinates specific to the part construction, (i.e. neglecting the coordinates related to print head movement only) and summarizes the coordinates in a text file.

A Python script was developed to create the finite element model within Abaqus. The Python script interprets the spatial coordinates compiled in the text file and defines the
length and width of each road, shown in Figure 1. The height of the roads were defined by the layer height specified in the G-code parameters. In this analysis, a road is defined as one linear segment of material that is deposited in the build area before the print head changes direction. The Python script assembles each road into the final geometry in the assembly module by copying the original road and offsetting the part according to the spatial coordinates listed in the text file. The code simultaneously tracks the sequence in which each road will be activated according to the print path. A road is activated using a *model change* instruction, simulating the addition of material during the printing process. The final geometry, containing all assembled roads, is then merged and meshed as a single part while maintaining individual road boundaries. Once the geometry and assembly is established, the heat transfer and stress models are created. These analyses are created separately for compatibility with the cure kinetics sub-model for thermosetting materials. The general framework is summarized in the schematic shown in Figure 2.

Figure 1. Interpretation of G-code spatial coordinates for road geometry and assembly.
2.2 *Heat Transfer Analysis*

The transient thermal analysis describes the cooling behavior which is driven by convective heat exchange with the environment, and contact with the platform after deposition. The convection surfaces on each road are individually selected using the spatial coordinates and road geometry as descriptors for the surface location. The script automatically applies the necessary convection surfaces on end roads, containing additional surfaces exposed to ambient air, and removes them from intermediate roads containing surfaces no longer exposed to ambient air. Convection surfaces with prescribed heat transfer coefficients and sink temperatures are individually created and activated for each road. A temperature boundary condition is applied to the platform part, assuming a constant and uniform temperature distribution. This thermal state could be applied to the road assembly as a simple boundary condition on the bottom surface of each road; however, the platform part was included to permit future variations in platform temperature
assumptions (e.g. radiation, nonuniform temperature distribution). The general types of boundary conditions applied in the heat transfer analysis are shown in Figure 3.

![Figure 3. General heat transfer boundary conditions.](image)

2.3 **Stress Analysis**

The script then copies the heat transfer model and replaces each heat transfer analysis step with a stress-displacement step, maintaining the road activation sequence. The results of the heat transfer analysis (i.e. temperature history) are imported into the stress analysis using a *predefined field*, which is introduced in the initial step of the analysis. The predefined field must be adjusted for each step in the stress analysis to map the individual road temperatures to the appropriate roads in the stress model. Each heat transfer boundary condition is replaced with a mechanical boundary condition in which each road on the first layer is assumed fixed to the platform in all directions. An investigation into this parameter in which shrinkage was permissible in the longitudinal (z), transverse (x), and in-plane (x and z) directions produced exaggerated deformations during printing. It was hypothesized that such stresses and displacements would cause the material to delaminate from the platform due to poor adhesion. In the last step of the stress analysis, the bottom surface constraints are removed, allowing the part to freely deform in space as a result of residual
stress, while new boundary conditions are imposed to prevent rigid body motion. The boundary conditions and assumptions are summarized in Figure 4.

![Figure 4. General stress analysis boundary conditions and assumptions.](image)

### 2.4 Geometric Parameters

To demonstrate the framework, a 2.5 inch by 0.25 inch rectangular coupon was modeled assuming a 90° short raster pattern with separate coupons consisting of one, two, or three layers, as shown Figure 5. Within the script the cross-section of the roads can be tailored for different geometries. In this work, rectangular and octagonal cross-sections were investigated. A rectangular cross-section assumes fully cohesive properties and ideal bond quality (i.e. coalescence) within the part, shown in Figure 6. The octagonal cross-section closely resembles the actual elliptical shape, with the inclusion of voids between each road, while also providing a planar surface to apply surface contacts for the adjacent roads, as shown in Figure 7. The rectangular cross-section was evaluated for the baseline model predictions. Given that the octagonal cross-section requires a more refined mesh, this geometry was evaluated as part of the sensitivity studies.
Figure 5. Final geometry for 1, 2, and 3 layer rectangular coupons.

Figure 6. Rectangular cross-section for individual road geometry.

Figure 7. Octagonal cross-section for individual road geometry.
Experimental methods were used to calibrate the thermoplastic model. Thermomechanical analysis (TMA) was conducted to determine the coefficient of thermal expansion as a function of temperature as part of the material property input. Thermal imaging was used to estimate the temperature of a road after being deposited from the nozzle for the initial road activation temperature in the analysis. The physical printing of the rectangular coupons and subsequent deflection measurement was used to evaluate the model predictions.

3.1 *Thermomechanical Analysis (TMA)*

All the properties for the ABS material were determined from the literature except the CTE values, which were acquired experimentally by Thermomechanical Analysis (TMA). In this test procedure, a probe rests on the surface of the sample, applying a small force of 0.5 Newtons, and measures the displacement, or expansion, as a function of temperature. The glass transition temperature ($T_g$) for ABS is around 100°C – 105°C. At this point, the material softens and the TMA probe penetrates the sample resulting in a sharp decrease in the apparent thermal strain [25], shown in Figure 8. Therefore, CTE measurements beyond the $T_g$ point are no longer valid using this method. The CTE was calculated by taking the slope from the reference temperature (25°C) to a single
temperature point in the graph, known as the secant CTE.

It is important to note that the ABS sample used in the TMA experiment was acquired from compression molded ABS and not from extruded ABS filament. During the deposition process, the polymer filament is heated and extruded through a smaller diameter nozzle, resulting in polymer chain alignment along the print direction within each road. FDM printed parts typically exhibit higher tensile strength compared to compression molded specimens due to this molecular orientation [5, 18]. When the deposited material is subsequently reheated in the TMA experiment, the polymer chains relax and contract, causing a positive jump in dimensional change. Although the sharp dimensional change is real, it is not an effect of CTE, but of polymer chain relaxation. Therefore, TMA must be conducted on compression molded samples instead of extruded ABS for accurate CTE measurements.

![Experimental TMA data](image)

Figure 8. Experimental Thermomechanical Analysis (TMA) data for compression molded ABS. The experimental data for CTE calculation is only valid up to the T\textsubscript{g} (~95°C).
3.2 Road Cooling

The model simulates the thermomechanical behavior after an entire road has been printed. Therefore, it was important to estimate the starting temperature of the roads as they are activated in the analysis. Although the nozzle temperature is set to 240°C, it was assumed that by the time a road is deposited onto the platform with a defined semi-solid shape, the road has significantly cooled. Using an Indigo System Merlin Mid thermal imaging camera outfitted with an ASIO 3-5 μm wavelength microscope objective from Janos Technologies, it was determined that a deposited road cooled to 120°C to 130°C in approximately 0.2 seconds, shown in Figure 9. The thermal imaging camera temperature range capability does not exceed 150°C, therefore accurate measurements could only capture the cooling after this point. A higher resolution camera is needed to capture the full cool down of filament exiting the extruder; therefore, these results are still preliminary.

![Figure 9. First layer cooling data of ABS printed roads from an infrared camera for two different print speeds (50 mm/s and 30 mm/s).](image_url)
3.3 Coupon Printing

To compare the results of the model predictions, experimental samples were printed using the nScrypt 3Dn-500 with ABS thermoplastic material. The nScrypt printer was equipped with an nFD Pump™ for FDM printing. The nFD Pump™ was outfitted with a 0.4 mm inner diameter ceramic dispenser tip. Slicing software was used to generate G-code for a rectangular coupon measuring 2.5 inch x 0.25 inch. The coupons were printed in a 90° short raster pattern for each layer. Typically an outline of the layer geometry is extruded preceding or following the infill pattern. In this print, the outline was omitted for a simple print path to simulate in the model. The layer thickness was set to 0.3 mm with a scanning speed of 30 mm/s. The samples were printed on a heated build plate set to 110°C with extruder temperature of 240°C, according to the manufacturer recommendations. Kapton tape was placed on the build platform to serve as a printing substrate, and was selected for its good adhesion to ABS. After print completion, power was shut off to the build platform heater, and the build platform was cooled before the print was removed from the Kapton substrate.

The single layer coupon appeared generally flat with minimal deformation while the two and three layer coupons exhibited a small bending deflection, shown in Figure 10 and Figure 11. These results were repeatable when printed on the nScrypt with the same printing parameters.
3.4 **Deflection Measurement**

Given the small scale prints and magnitude of deflection, the topography of the ABS coupons were measured with a Keyence LJ-V7080 laser scanner mounted on the nScrypt gantry. The scan records and summarizes the spatial coordinates in a text file which is then post-processed in a Matlab script to reduce noise in the data. A Menger triangle approach, where the curvature is estimated by the side lengths of a triangle, was used to approximate the maximum deflection of the printed coupons. The curvature based on this method is given by
\[ c(x, y, z) = \frac{1}{R} = \frac{4A}{|x - y||y - z||z - x|} \]

where \( R \) is the radius and \( A \) is the area of the triangle spanned by side lengths \( x, y, \) and \( z \).

Multiple points along the middle of the coupons were evaluated to estimate the maximum curvature. However, due to the amount of noise in the laser scan, a significant amount of error was acquired. The calculated maximum curvature or deflection is summarized in Figure 12.

Figure 12. Maximum deflection (mm), or curvature, for each experimentally printed ABS coupon consisting of one, two, and three layers.
CHAPTER 4
THERMOPLASTIC MODEL

The assumptions and boundary conditions for the thermoplastic model correspond to the experimental conditions used for the physical printing of the ABS coupons and are referred to as the baseline model conditions. Assumptions for the material property CTE, road geometry, and thermal boundary conditions are discussed.

4.1 Material

ABS is a common material used in FDM and therefore an appropriate choice for demonstrating the framework for a thermoplastic polymer. Temperature dependent material properties found in the literature for specific heat, and flexural modulus were used in the sequential thermo-mechanical model. Temperature dependent coefficient of thermal expansion values were calculated from the TMA experiment. A final point for the CTE was estimated for the road activation temperature beyond the $T_g$ based on the typical behavior of an amorphous material. Amorphous materials have no melting point, and therefore softens when heated above $T_g$. The material becomes progressively less viscous, resulting in a steep increase in expansion as it reaches the viscoelastic liquid state, shown in Figure 13. Based on this typical response, the change in dimension in the viscoelastic liquid state was approximated for the road activation temperature (120°C), shown in Figure 14. A summary of the material properties used for ABS are shown in Table 1.
Figure 13. Changes in specific volume in an amorphous polymer with increasing temperature [26].

Figure 14. Experimental TMA data from compression molded ABS sample along with incremental points where the secant CTE was calculated. The figure also shows the approximated thermal strain at the road activation temperature (120°C).
### Table 1. Material properties for ABS.

<table>
<thead>
<tr>
<th>Conductivity (W/m K)</th>
<th>Density (kg/m³)</th>
<th>Specific Heat (kJ/kg K)</th>
<th>CTE* (°C⁻¹)</th>
<th>Flexural Modulus (MPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>1200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 °C 1.62</td>
<td>25°C 7.41E-05</td>
<td>0 °C 2500</td>
<td>0 °C 0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>105 °C 1.62</td>
<td>30°C 9.95E-05</td>
<td>80 °C 2000</td>
<td>80 °C 0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120 °C 3.00</td>
<td>40°C 1.08E-04</td>
<td>100 °C 1000</td>
<td>100 °C 0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50°C 1.23E-04</td>
<td>120°C 11</td>
<td>120°C 0.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60°C 1.38E-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70°C 1.50E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>80°C 1.61E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90°C 1.69E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95°C 1.65E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>120°C 1.79E-04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 4.2 Geometry

The printing of single layer, two layer, and three layer rectangular coupons with a rectangular cross-section for all roads is first analyzed in the baseline model. The octagonal cross-section is evaluated as part of the sensitivity study. Each road measured 0.4 mm in width and 6.35 mm in length, as determined by the G-code spatial coordinates for the print path. The thickness or height of each road was determined by the layer height specified in the G-code. The baseline mesh for this geometry consists of 64 total linear elements with four elements through the thickness of the road in order to accurately capture the bending stresses. The geometry and mesh for a single rectangular road is shown in Figure 15.
4.3 *Thermal Cycle*

Thermal conditions for the ABS model approximate the parameters used in the experimentally printed specimens. An initial temperature of 120°C is specified for the newly activated roads. The platform and ambient air temperatures, 110°C and 25°C respectively, are assumed uniform and constant. In this baseline model, radiation or local reheating of the platform from the deposited roads is not considered. Convection is applied to the exposed surfaces of each road segment by applying a nominal heat transfer coefficient of 10W/m²K (i.e., assuming minimal forced air flow) with a sink temperature of 25°C. After the deposited roads are fully assembled, the temperature of the platform is ramped down to room temperature. An overview of the heat transfer boundary conditions and assumptions given in Figure 16.
Figure 16. Heat transfer analysis boundary conditions and assumptions for the thermoplastic ABS model.
CHAPTER 5
BASELINE THERMOPLASTIC RESULTS

5.1 Heat Transfer Results

The first deposited layer in the analysis demonstrates rapid cooling due to the tie constraint between the layer and the build plate. Throughout the deposition process, the temperature of the first layer remains close to the prescribed platform temperature of 110°C. As the thickness of the part increases with increasing number of layers, a larger thermal gradient develops as the temperature of these roads becomes more affected by convection with the cooler ambient air, shown in Figure 17.

Figure 17. Temperature gradient (°C) during printing in three layer ABS coupon (top) and single layer ABS coupon (bottom).

5.2 Stress-Deformation Results

Within the stress model, residual stresses and deformations throughout the printing
process are predicted. The results of the stress analysis show a positive (upward) deflection for the single layer baseline predictions while the two and three layer parts exhibit a negative (downward) deflection, shown in

Figure 18. Examining the residual stresses in the +x direction, shown in Figure 19, shows a slightly higher tensile stress on the top surface than the bottom surface, resulting in an upward deflection, shown in Figure 20.

Figure 18. ABS baseline model predictions for 1, 2, and 3 layer models.
Comparing the ABS model predictions with the experimentally printed specimens show a similar trend for the deflection magnitudes in the two and three layer specimens. However, the single layer model greatly over-predicts the deflection magnitude and direction when compared to the experimentally printed single layer, which appeared nearly flat. Discrepancies within the single layer predictions may be due to physical phenomena occurring in the initial layer. For instance, a single thin layer of material may experience
more uniform temperatures through the thickness during the deposition process and cooling process. This may result in a lower residual stress state and subsequent lower deformation in the experimental specimens which is not captured in the model framework. The model predictions and experimentally measured values for the ABS coupons are summarized in Figure 21 and Table 2. The model run times for the heat transfer and stress analyses with the baseline mesh are summarized in Table 3.

![Figure 21. Comparison of model predictions with experimentally measured values for maximum deflection in ABS coupons.]

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Experimental (mm)</th>
<th>Baseline Model Predictions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.012</td>
<td>0.615</td>
</tr>
<tr>
<td>2</td>
<td>-0.210</td>
<td>-0.068</td>
</tr>
<tr>
<td>3</td>
<td>-0.410</td>
<td>-0.228</td>
</tr>
</tbody>
</table>
Table 3. Heat transfer and stress analysis run times for the baseline mesh.

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th># Linear Elements</th>
<th>HT Analysis Run Time</th>
<th>Stress Analysis Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10,251</td>
<td>3 min</td>
<td>4 min</td>
</tr>
<tr>
<td>2</td>
<td>20,427</td>
<td>16 min</td>
<td>17 min</td>
</tr>
<tr>
<td>3</td>
<td>30,603</td>
<td>33 min</td>
<td>40 min</td>
</tr>
</tbody>
</table>
CHAPTER 6
THERMOPLASTIC SENSITIVITY STUDIES

The objective for performing sensitivity studies is to determine how different parameters within the model affect the overall outcome of the analysis, i.e. residual stress and deflection in the coupon. This study is also necessary to prioritize the parameters that have the greatest effect on the model and how inaccuracies in individual parameters affect the model. The parameters chosen for the sensitivity study were based on key assumptions or areas of uncertainty determined in the baseline model. These parameters include the estimated CTE at the activation temperature of 120°C, the temperature dependent elastic modulus, the thermal boundary condition between the platform and bottom surface of the roads, the heat transfer coefficient associated with the convection surfaces, and the mesh density.

6.1 Material Properties

6.1.1 Coefficient of Thermal Expansion (CTE)

As previously discussed, the CTE was calculated as the secant slope from a reference temperature of 25°C up to the T_g where the results of the thermomechanical analysis (TMA) were still valid. A last value for the CTE at the road activation temperature (120°C) was estimated based on the behavior of a typical amorphous material. The thermal strain curve was increased 10, 20, and 50 percent to reflect the increase in CTE. The
thermal strain curves for the CTE variation are shown in Figure 22 and Table 4.

![Figure 22. Thermal strain and subsequent CTE variation for sensitivity study of ABS material.](image)

**Table 4. Summary of CTE variations for sensitivity study of ABS material.**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Baseline CTE (°C⁻¹)</th>
<th>CTE +10% (°C⁻¹)</th>
<th>CTE +20% (°C⁻¹)</th>
<th>CTE +50% (°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>7.41E-05</td>
<td>8.147E-05</td>
<td>8.888E-05</td>
<td>1.111E-04</td>
</tr>
<tr>
<td>30</td>
<td>9.95E-05</td>
<td>1.094E-04</td>
<td>1.194E-04</td>
<td>1.492E-04</td>
</tr>
<tr>
<td>40</td>
<td>1.08E-04</td>
<td>1.192E-04</td>
<td>1.300E-04</td>
<td>1.625E-04</td>
</tr>
<tr>
<td>50</td>
<td>1.23E-04</td>
<td>1.355E-04</td>
<td>1.478E-04</td>
<td>1.847E-04</td>
</tr>
<tr>
<td>60</td>
<td>1.38E-04</td>
<td>1.514E-04</td>
<td>1.651E-04</td>
<td>2.064E-04</td>
</tr>
<tr>
<td>70</td>
<td>1.50E-04</td>
<td>1.653E-04</td>
<td>1.804E-04</td>
<td>2.255E-04</td>
</tr>
<tr>
<td>80</td>
<td>1.61E-04</td>
<td>1.772E-04</td>
<td>1.933E-04</td>
<td>2.417E-04</td>
</tr>
<tr>
<td>90</td>
<td>1.69E-04</td>
<td>1.857E-04</td>
<td>2.026E-04</td>
<td>2.532E-04</td>
</tr>
<tr>
<td>95</td>
<td>1.65E-04</td>
<td>1.814E-04</td>
<td>1.979E-04</td>
<td>2.474E-04</td>
</tr>
<tr>
<td>120</td>
<td>1.79E-04</td>
<td>1.970E-04</td>
<td>2.149E-04</td>
<td>2.686E-04</td>
</tr>
</tbody>
</table>

The results of the CTE variation show an increasing trend in deflection magnitude with the higher CTE values for all layer models. The higher CTE values result in higher
residual stresses during the cooling process [29]; therefore it was expected that the increase in CTE values would result in increasing deflection. A summary of the experimental results and model predictions for the baseline conditions and CTE sensitivity are shown in Figure 24 and Table 5.

Figure 23. Contour plot of x-direction residual stresses (Pa) in the center of rectangular coupon for the single layer case with a 10 percent increase in CTE. The results indicate a higher residual stresses compared to the baseline model prediction shown Figure 19.

Figure 24. Model predictions for maximum deflection (mm) in ABS coupons with varying coefficient of thermal expansion (CTE) values.
Table 5. Model predictions for maximum deflections (mm) for varying CTE.

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Experimental (mm)</th>
<th>Baseline (mm)</th>
<th>CTE+10% (mm)</th>
<th>CTE+20% (mm)</th>
<th>CTE+50% (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.012</td>
<td>0.615</td>
<td>0.619</td>
<td>0.740</td>
<td>0.859</td>
</tr>
<tr>
<td>2</td>
<td>-0.210</td>
<td>-0.068</td>
<td>-0.070</td>
<td>-0.082</td>
<td>-0.097</td>
</tr>
<tr>
<td>3</td>
<td>-0.410</td>
<td>-0.228</td>
<td>-0.232</td>
<td>-0.274</td>
<td>-0.322</td>
</tr>
</tbody>
</table>

6.1.2 Elastic Modulus (E)

Literature reported values for elastic or Young’s modulus as a function of temperature can vary slightly from various sources. To investigate the significance of this material property, the storage modulus values were shifted ±10%, shown in Figure 25. A 10% increase in modulus values corresponds to a 10% higher stress state prior to the tool removal step. However, this difference in stress was not great enough to affect the end part deflection. The same trend is shown for the 10% decrease in modulus. This is expected given the linear elastic model framework. The results of the storage modulus sensitivity study are summarized in Figure 26.

Figure 25. Storage modulus (E’) variation for ABS sensitivity study.
Figure 26. Model predictions for maximum deflection (mm) in ABS coupons with varying storage modulus (E’) values.

6.2 Thermal Boundary Conditions

6.2.1 Conduction between Roads and Platform

The tie constraint between the bottom of each road and the platform assumes these nodes on both surfaces are joined. Therefore, when each road is activated in the print sequence a thermal gradient from the platform temperature and print temperature is automatically implemented, shown in Figure 27. This results in a much faster cool down rate on the bottom surface and through the thickness of each road.
Various thermal conditions applied to the bottom surface of the layer roads were investigated to determine the effect of cooling originating from the bottom surface of the roads in contact with the platform. The tie constraint represents one end of the spectrum for immediate cooling to 110°C. The opposite extreme is to remove the tie constraint all together and model the bottom surface of the first layer roads as insulated. In order to examine conditions between these constraints, a convection surface was applied to the bottom surface specifying the sink temperature as 110°C. The heat transfer coefficient (HTC) was then varied to simulate environments between the tie constraint and without tie constraint conditions. A HTC set to 1000 W/m²K results in a rapid cool down of this surface, similar to a tie constraint, while a HTC set to 100 W/m²K results in a slower cool down similar to the removed tie constraint condition, shown in Figure 28.
Figure 28. Nodal temperatures (°C) in ABS coupons for varying thermal conditions applied to bottom surface of first layer roads. Nodal temperature history for initial cool down retrieved from the center node in the third deposited road.

The results of this variation in thermal boundary condition on the bottom surface of the first layer roads are summarized in Figure 29 and Table 6. The deflection magnitude in the single layer model is not significantly affected by the different thermal boundary conditions; however, it does result in a change in the direction of deflection from positive to negative. In both multi-layered cases where the tie constraint was either removed or replaced with a convection surface follow a distinct trend of increasing deflection magnitude with a slower cool down rate. These results show that the system is highly sensitive to the cool down rate of the bottom surface. It can also be concluded that a more representative description of the bottom surface boundary condition may lie somewhere between the tie constraint condition and an applied convection condition with a high HTC.
Figure 29. Model predictions for maximum deflection (mm) in ABS coupons with varying thermal conditions applied to the bottom surface of first layer roads.

Table 6. Model predictions for maximum deflections (mm) for varying thermal conditions on bottom surface of roads.

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Experimental (mm)</th>
<th>Baseline (mm)</th>
<th>HTC=1000 W/m²K (mm)</th>
<th>HTC=300 W/m²K (mm)</th>
<th>HTC=100 W/m²K (mm)</th>
<th>No Tie Constraint (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.012</td>
<td>0.615</td>
<td>-0.340</td>
<td>-0.344</td>
<td>-0.305</td>
<td>-0.270</td>
</tr>
<tr>
<td>2</td>
<td>-0.210</td>
<td>-0.068</td>
<td>-0.825</td>
<td>-1.220</td>
<td>-1.850</td>
<td>-6.094</td>
</tr>
<tr>
<td>3</td>
<td>-0.410</td>
<td>-0.228</td>
<td>-0.730</td>
<td>-1.160</td>
<td>-2.170</td>
<td>-4.717</td>
</tr>
</tbody>
</table>

6.2.2 Heat Transfer Coefficient with Environment

A study estimated that the heat transfer coefficient (HTC) for convection can range between 10-140 W/m²K [30]. In the baseline model, it was assumed forced convection was minimal and described by a low HTC of 10 W/m²K. This assumption was coupled with a maximum conduction with the platform using a tie constraint between the surfaces in contact. To evaluate the effect of the convective cooling on the residual stress and deformation, a new HTC of 70 W/m²K was implemented. Evaluating the heat transfer
analysis using the new HTCs shows a faster cool down rate, as shown in Figure 30. The temperature profiles in Figure 30 were extracted from a single node at the center of a first-layer road. The higher HTC value of 70 W/m²K not only cools at a faster rate but also cools to a lower temperature as the cooling becomes more dominated by convection with the air than the imposed tie constraint with the platform. This is also evident in Figure 31 where an increase in the thermal gradient through the thickness of the roads is depicted.

![Figure 30](image)

Figure 30. Cool down temperatures in ABS coupons for varying heat transfer coefficient (HTC, [W/m²K]).

![Figure 31](image)

Figure 31. Temperature gradient (°C) during print for single layer with HTC = 70 W/m²K (top) and single layer with HTC = 10 W/m²K (bottom) at the same time step.
The results of this study show an increase in the maximum deflection with increasing HTCs. Additionally, the increase in the HTC from the baseline model (HTC = 10 W/m²K) to 30 W/m²K resulted a significant change in deflection magnitude and the deflection direction for the single layer model, shown in Figure 32. A higher HTC value for the air convection may be more representative of the system given the small scale of the roads. A summary of the sensitivity results are shown in Figure 33 and Table 7.

![Figure 32. Downward deflection (meters) in the y-direction (U2) for single layer ABS model. Deflection is shown with a scale factor of 5.](image)

![Figure 33. Model predictions for maximum deflection (mm) in ABS coupons with varying heat transfer coefficients (HTC) applied to the exposed surfaces of each road (does not include bottom surface).](image)
Table 7. Model predictions for maximum deflections (mm) for various convective heat transfer coefficients (HTC) exposed to the air environment.

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Experimental (mm)</th>
<th>Baseline (mm)</th>
<th>Air HTC=30 W/m²K (mm)</th>
<th>Air HTC=70 W/m²K (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.012</td>
<td>0.615</td>
<td>-0.077</td>
<td>-1.030</td>
</tr>
<tr>
<td>2</td>
<td>-0.210</td>
<td>-0.068</td>
<td>-0.897</td>
<td>-2.659</td>
</tr>
<tr>
<td>3</td>
<td>-0.410</td>
<td>-0.228</td>
<td>-1.250</td>
<td>-2.636</td>
</tr>
</tbody>
</table>

6.3 Mesh and Road Geometry

Typically, a mesh convergence study is initially performed to minimize the discretization error and determine the solution accuracy. In this case, the refinement of the mesh directly impacts the cooling behavior due to the imposed boundary conditions (e.g. tie constraint between roads and platform). The number of integration points between the bottom surface of the roads containing surface tie constraint and top integration points where convection is applied impacts the through-thickness cooling, shown in Figure 34. The octagonal cross-section is included in the mesh sensitivity study since it requires a more refined mesh in order to reduce the aspect ratio for each element while maintaining about four elements through the thickness of the road.
Figure 34. Through thickness road cooling (°C) as a function of mesh density.

The results of the coarse and fine meshing techniques show vastly different results for the predicted deflection magnitude and direction of the deflection, shown in Figure 35 and Table 8. As determined from the previous studies, the model is highly sensitive to thermal history within the road which is directly affected by the density of the mesh. However, these results show a correlation between the fine mesh in the rectangular cross-section and the octagon cross-section which is expected due to the similar mesh density in both cases.
Table 8. Model predictions for maximum deflection (mm) in ABS coupons with varying mesh refinement.

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Experimental (mm)</th>
<th>Baseline (mm)</th>
<th>Coarse Mesh Rectangle (mm)</th>
<th>Fine Mesh Rectangle (mm)</th>
<th>Baseline Octagon (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.012</td>
<td>0.615</td>
<td>-0.886</td>
<td>1.190</td>
<td>1.020</td>
</tr>
<tr>
<td>2</td>
<td>-0.210</td>
<td>-0.068</td>
<td>-0.590</td>
<td>0.100</td>
<td>0.151</td>
</tr>
<tr>
<td>3</td>
<td>-0.410</td>
<td>-0.228</td>
<td>-0.755</td>
<td>-0.106</td>
<td>-0.113</td>
</tr>
</tbody>
</table>

6.4 Combination of Factors

From the sensitivity studies of individual main effects, increasing the air heat transfer coefficient adjustment to 30 W/m²K and the bottom surface convection (HTC=1000 W/m²K) replacing the thermal tie constraint showed the most improvement in predicting the maximum deflection. In particular, both studies predict a negative deflection for the single layer print as opposed to the large positive deflection in the baseline model. Both of these factors were applied to the baseline mesh. However, combining these factors
amplified the predicted deflection magnitude for all cases, shown in Figure 36.

Figure 36. Model predictions for maximum deflection (mm) in ABS coupons with combined factors.
CHAPTER 7

THERMOSET MODEL

The assumptions and boundary conditions for the thermosetting polymer and PMC model are based on the previous efforts from Compton and Lewis which demonstrated the printability for a fiber reinforced thermosetting epoxy ink [20].

7.1 Material

Thermosetting neat resin and thermosetting composites with carbon fiber reinforcement were evaluated using Convergent Manufacturing Technology’s COMPRO Simulation Software. The thermosetting material used in the analyses is a built-in COMPRO material model for Hexcel 8552 neat resin. To the author’s knowledge, this particular thermosetting material is not currently being developed for FDM use and was chosen arbitrarily to demonstrate the linkage between the COMPRO code and stepwise modeling which involves time and temperature dependency for evolving material properties. Modeling a thermosetting resin system using COMPRO does not require any material property inputs from the user. The material sub-models for each material property are calibrated using test data for the current temperature and transmitted to Abaqus. Properties supplied by COMPRO to the Abaqus solution include cure rate, T_g, resin modulus, resin Poisson’s ratio, cure shrinkage factor, and CTE. The COMPRO material models are not presented here; details can be found in the COMPRO Model Documentation manuals [28].

The COMPRO material properties can be tailored within the Extensible Markup
Language (xml) file for a specific material. Here, the fiber volume fraction was adjusted to 0.0001 to account for a neat resin model and 0.10 for a composite, similar to the fiber content used in the printable thermosetting epoxy ink [20]. Extrusion of the epoxy ink with chopped carbon fibers results in semi-aligned fibers in the print direction. Given that the COMPROMO material models are based on unidirectional laminate micromechanics, the modulus was also tailored to account for the semi-aligned chopped fibers within the laminate. Using the reported elastic modulus from this study along with literature based results for semi-aligned discontinuous fibers, the modulus was estimated in the COMPROMO xml file, resulting in a 75% reduction compared to unidirectional laminates. This reduction in modulus corresponds to a reinforcement efficiency ranking between 0.375 and 0.2 for chopped fibers aligned within a specific plane and any direction within a 3D space [29, 30]. This reinforcement efficiency value can be applied to the fiber term in the rule of mixtures equation to estimate mechanical properties as a function of fiber volume fraction and constituent material properties. This is shown by

\[ E_c = E_m(1 - V_f) + KE_fV_f \]  

where \( E_c \) is the elastic modulus for the composite, \( E_m \) is the elastic modulus for the matrix, \( E_f \) is the elastic modulus for the fiber, \( V_f \) is fiber volume fraction for the composite, and \( K \) is the efficiency value which ranges from 1 for perfectly aligned discontinuous fibers to 0.2 for discontinuous fibers randomly aligned within a 3D space.

7.2 Geometry

Similar to the thermoplastic model, the printing of rectangular coupons is simulated. In this work, only the octagonal cross-section for each road is analyzed for the thermosetting
material. The mesh for this geometry consists of 1071 linear elements, shown in Figure 37. This level of refinement was necessary to reduce the aspect ratio for each element while maintaining about four elements through the thickness of the road. A three-layer model for the neat resin is first analyzed to demonstrate the model compatibility with the COMPRO Simulation Software. Next, a two-layer coupon is modeled for a symmetrical print where all fibers are aligned in the 90° raster pattern (z-direction) and an unsymmetrical print involving a 90°/0° raster pattern, shown in Figure 38 and Figure 39, respectively.

Figure 37. Mesh for a single road with an octagonal cross-section.
7.3 Thermal Cycle

The thermoset model assumes a uniform temperature throughout the printing process by specifying the ambient, extrude, and platform temperature as 25°C. This isothermal
condition was based on the assumption that a rheological shear thinning modifier is added to the resin system for printability, similar to the Compton and Lewis formulation [20]. The fully assembled coupon is then post-cured by prescribing the manufacturer cure cycle for Hexcel 8552, shown in Figure 40, to the convection surfaces within the structure. The void space between the multiple layers is not included as a convection surface and assumed insulated throughout the analysis, shown in Figure 41. While the thermosetting resin is formulated for autoclave curing requiring both elevated temperature and pressure, only the cure temperatures were implemented to show the cure kinetics and final degree of cure.

![Manufacturer cure cycle for Hexcel 8552 material.](image)

Figure 40. Manufacturer cure cycle for Hexcel 8552 material.
Figure 41. Heat transfer boundary conditions for the octagonal cross-section.
Neat resin and filled carbon fiber epoxy material systems were evaluated using the Convergent Manufacturing Technology COMPRO Simulation Software in conjunction with the 3D finite element modeling framework. Given the isothermal state of the material during the deposition process in both cases, the stepwise road activation sequence was bypassed for computational efficiency. The predetermined part geometry consisting of individual roads in the shape of an octagonal prism were assigned an initial temperature state of 25°C by defining a predefined field in the heat transfer analysis. The second analysis step consists of the thermal post-cure in which the outer convective surfaces were prescribed the cure cycle with a heat transfer coefficient (HTC) of 50 W/m²K. The results of the heat transfer analysis were imported into the stress analysis.

8.1 Neat Resin

Within the heat transfer analysis, the fully assembled coupon was cured according to the manufacturer cure cycle resulting in a final degree of cure of 0.89, shown in Figure 42. The residual stress and subsequent deformation increased with each layer resulting in maximum compressive stress and deflection in the top edges of each coupon. Given the thermal conditions during printing and small thermal gradient between the ambient air and platform during the cure, shown in Figure 43, the end deformation was mainly in the form of in-plane shrinkage due to cooling, shown in Figure 44.
Figure 42. Nodal temperature (°C) and degree of cure as a function of cure cycle and time (seconds).

Figure 43. Thermal gradient (°C) in neat Hexcel 8552 material during the first ramp in cure cycle with temperature gradient due to temperature lag applied to tooling.

Figure 44. Deformation (meters) in the two layer neat resin Hexcel 8552 coupon.

8.2 Polymer Matrix Composite

Two print patterns or fiber orientations were evaluated in the carbon fiber filled
epoxy system. The most basic case incorporates the same print path evaluated in the ABS model, a 90° short raster pattern. In this case, the fiber direction was specified in the z-direction assuming fiber alignment along the length of each road.

8.2.1 Two Layer, 90° raster pattern model

The inclusion of 10% volume fraction of carbon fiber with an effective modulus to represent semi-aligned chopped fibers produced a similar trend compared to the neat resin model. Due to the isothermal conditions during printing and symmetrically aligned fibers within the part, minimal deflections were predicted. The deflection in the y-direction are shown to scale in Figure 45. These deformations are mainly due to resin shrinkage during the cure cycle.

![Figure 45. Contour plot of the bending deflection (in meters) in the y-direction for the two layer rectangular coupon with 90° print pattern. The simulated material is Hexcel 8552 with chopped AS4 fibers (V_f = 0.10)](image)

8.2.2 Two layer, 90°/0° raster pattern model

A two layer FDM part consisting of an alternating print path in the 90° raster pattern in the first layer and 0° raster pattern in the second layer is representative of an unsymmetric [0/90]_T cross-ply, shown in Figure 46. Following the post cure cycle, the composite structure deforms similarly to an unsymmetric laminate with a large bending deflection in
y-direction, shown in Figure 47. This deflection is due to the transverse CTE, perpendicular to the fibers, which dominates the residual stresses within the part. As the matrix tries to contract due to resin shrinkage, the bottom surface is constrained by both the platform and the second layer perpendicular fibers creating in a tensile stress on the bottom layer resulting in the large downward deflection. These displacements are shown to scale in Figure 47.

The analysis shows how the print path and subsequent fiber alignment can alter the end part deflection after curing, causing behavior similar to that of a traditional composite laminate. From these results, process modeling can be used to understand the underlying physics in determining effective print paths to reduce the residual stress and warping after curing.

Figure 46. Two layer rectangular coupon printed in a 90° and 0° print pattern. The simulated material is Hexcel 8552 with chopped AS4 fibers ($V_f = 0.10$).

Figure 47. Contour plot of the bending deflection (in meters) in the y-direction for the two layer rectangular coupon with 90° and 0° print pattern. The simulated material is Hexcel 8552 with chopped AS4 fibers ($V_f = 0.10$).
9.1 *Summary*

In this work, a model framework for FDM thermal history and residual stress prediction was developed. A Python script was created to automatically generate a 3D finite element thermo-mechanical model including step-dependent thermal and mechanical boundary conditions, with elements activated sequentially to simulate the printing process. The model was first applied to ABS parts, to allow comparisons of the predictions to experimentally printed parts. The methodology was demonstrated for a simple rectangular coupon with continuous roads and activated according to a 90° short raster pattern. Using the initial sequentially coupled heat transfer and stress analyses, the preliminary model simulated the deflection in the rectangular coupon due to residual stresses.

The model accurately captured the increasing deflection magnitude from two layers to three layers as measured from the experimentally printed specimens, however, the single layer model significantly over-predicted the deflection magnitude and direction. The deviation in the model prediction may be due to a different physical event occurring in the thin single layer, such as a more uniform temperature gradient during the printing and cooling process. This hypothesis was justified by the preliminary sensitivity studies in which changing the rate of cooling reversed the direction of deflection in the single layer model prediction that more accurately correlates with the experimental result.
The modeling framework was next applied to thermosetting Hexcel 8552 epoxy material system in which neat resin and oriented carbon fiber-filled epoxy composites were modeled. The simulation of a two layer 90° and 0° raster pattern 3D printed part resulted in a large bending deflection characteristic of a thin unsymmetrical composite laminate.

9.2 Future Efforts

The proposed modeling framework proved to be successful in accurately capturing trends in deflection when compared to experimentally printed ABS samples. In addition, the predicted deflection accuracy improved with the more realistic boundary conditions evaluated in the sensitivity study. In this sensitivity study, five main effects (storage modulus, CTE, convection coefficient on exposed surfaces, the thermal condition on the first layer bottom surface, and mesh density) were evaluated. Ongoing work will analyze the interaction between these main effects in a full factorial analysis on the model predictions for residual stress and deformation.

Although the high-fidelity approach of modeling individual roads as the part is printed results in a more computationally expensive analysis, the added flexibility in the model framework allows for future research in incorporating additional complexities. The current modeling framework demonstrated versatility in describing the road shape and size with rectangular or octagonal road cross-sections. This flexibility can be extended by further discretizing individual roads into road segments for larger prints. Similarly, the geometry and size of the individual roads or road segments are tailorable for other extrusion-based additive processes such as Big Area Additive Manufacturing (BAAM).

Additional experimental characterization techniques can be investigated to further improve the model. Dynamic Mechanical Analysis (DMA) is used to capture the
viscoelastic response of the material, which can be included in the stress and deformation analysis. Additionally, optical dilatometry can be performed to measure the material CTE above the T_g without any measurement probe interference, providing more accurate thermal expansion properties. Parameterized contact conditions to estimate adhesion or delamination from the build platform can also be included in the analysis based on experimental data. Thermal conditions such as radiation from the platform or nozzle head can also be incorporated in the model from thermal imaging techniques.

Although much work remains to be done, the proposed modeling framework developed in this thesis demonstrates significant accuracy in modeling and predicting the FDM process for a basic 3D printed material. In addition, it is also formulated to apply traditional composite modeling techniques to the process modeling of additively manufactured thermosetting polymers and polymer matrix composites. To the author’s knowledge, no other work has coupled a cure kinetics model to a 3D finite element analysis for additively manufactured parts. The proposed model demonstrates how process modeling is a useful tool for future development in advanced manufacturing techniques.
REFERENCES


