Development of a Thermo-Mechanical Finite Element Framework for Multi-Layer Fused Filament Fabrication of Polypropylene

Luke Gilmour[1,*], Anto Antony Samy[1], Alistair McIlhagger[1]

[1] School of Engineering, Ulster University, Northern Ireland
*Correspondence: Gilmour-L7@ulster.ac.uk

ABSTRACT

Fused filament fabrication of semi-crystalline polymers is influenced by complex thermal behaviour that contributes to residual stress and part distortion. This work presents the development of a two-dimensional thermo-mechanical finite element framework for modelling the multi-layer deposition of polypropylene using COMSOL Multiphysics. The model combines sequential material activation with a moving Gaussian heat source to represent the deposition process and captures the transient thermal history. The predicted temperature response demonstrates the characteristic reheating associated with successive layer deposition, with peak temperatures at the layer centres increasing from approximately 142 °C in the first layer to 218 °C in the fourth layer. This work provides a baseline framework for future development towards a fully integrated thermo-mechanical model for semi-crystalline polymers during fused filament fabrication.

KEYWORDS: fused filament fabrication; polypropylene; finite element modelling; thermo-mechanical modelling; additive manufacturing

1. INTRODUCTION

Fused filament fabrication (FFF) has become a widely used additive manufacturing process because of its relatively low cost, accessibility and ability to produce complex geometries [1]. Although much of the early research focused on amorphous polymers, there is increasing interest in semi-crystalline materials such as polypropylene (PP) due to their favourable mechanical properties, chemical resistance and low density [2]. A major challenge, however, is the crystallisation that occurs during cooling, which causes non-uniform shrinkage and can lead to residual stresses and part distortion [2,5,6].

Finite element modelling has become an important tool for investigating the thermal and mechanical behaviour of components produced by FFF [3,4]. Modelling approaches that incorporate sequential material deposition, moving heat sources and thermo-mechanical coupling can reproduce the transient thermal conditions that develop during printing and their influence on residual stress and warpage [3,4,7]. As these approaches continue to develop, increasing attention is being directed to incorporating additional process physics in order to improve model fidelity.

This paper presents the development of a baseline two-dimensional thermo-mechanical finite element framework for multi-layer FFF of polypropylene using COMSOL Multiphysics. The model employs sequential material activation and a moving Gaussian heat source to replicate the deposition process while capturing the evolution of temperature, residual stress and deformation throughout the build. This work represents the first stage of a broader research project aimed at developing an integrated modelling framework for semi-crystalline polymers, linking pre-deposition process modelling with post-deposition thermo-mechanical analysis.

2. MATERIALS AND METHODS

A two-dimensional thermo-mechanical finite element model was developed in COMSOL Multiphysics to simulate the layer-by-layer deposition of polypropylene. The model consists of an aluminium build plate and four deposited PP layers, each 0.5 mm thick, providing a simplified representation of the FFF process. The current work is limited to a two-dimensional cross-section and forms the baseline for future three-dimensional model development.

The deposition process was represented using sequential material activation, whereby elements are progressively activated to replicate the deposition of the filament during fabrication. A moving Gaussian heat source was applied to the active deposition region, allowing the transient thermal history associated with material deposition, cooling and reheating to be captured. Heat transfer between the deposited material, previously printed layers and the build plate was modelled using transient heat conduction, allowing the transient temperature field throughout the deposition process to be captured.

The temperature field was coupled with solid mechanics to investigate the development of thermally induced residual stresses and deformation during printing. Thermal expansion was used to represent the contraction of the deposited material during cooling, enabling the development of residual stresses and deformation. A time-dependent solution was then used to calculate the thermo-mechanical response throughout the deposition process.

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3. RESULTS

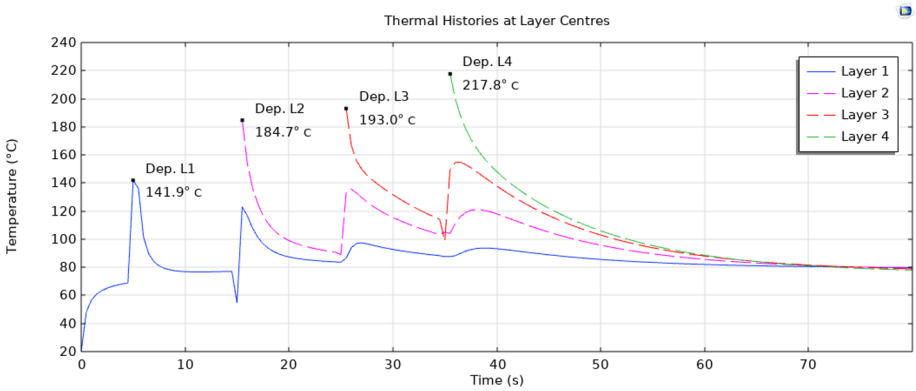


Figure 1. Temperature histories at the centre of each deposited layer.

The repeated temperature peaks in Figure 1 correspond to the addition of successive layers, with previously deposited material reheated as each new layer is introduced. Cooling resumes between deposition events, producing the cyclic thermal response associated with multi-layer FFF. The layer-centre peak temperatures increased progressively from 141.9 °C in Layer 1 to 217.8 °C in Layer 4.

4. DISCUSSION

Reproducing the transient thermal history during deposition provides the basis for further development of the modelling framework. The predicted temperature cycles reflect the repeated heating and cooling experienced during multi-layer FFF and provide the thermal conditions required for subsequent thermo-mechanical analysis [3]. Although the current work focuses on the thermal response, the framework establishes the basis for future development towards a more comprehensive multi-physics model for semi-crystalline polymers.

5. CONCLUSION

A thermo-mechanical finite element framework has been developed to model the multi-layer fused filament fabrication of polypropylene. The current model captures the transient thermal behaviour during deposition using sequential material activation and a moving Gaussian heat source. This provides the basis for extending the framework to 3D, include additional physics and improve the representation of the thermo-mechanical behaviour of semi-crystalline polymers during FFF.

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