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Estimation of Inter-Layer Deposition Delay for Improved FDM Part Quality using Thermal Analysis

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Abstract

Fused deposition modeling (FDM) is widely used in additive manufacturing; however, part quality is significantly influenced by thermal history during layer-wise deposition. In particular, improper control of inter-layer deposition timing can lead to defects such as warping, residual stresses, and weak inter-layer bonding. Although several studies have investigated thermal behavior in FDM, limited attention has been given to translating thermal analysis into practical process guidelines. In this study, a transient thermal model based on the element birth–death technique is developed using finite element analysis to simulate the sequential deposition of an ABS filament. The model captures the temperature evolution of the deposited layer and its cooling behavior under convective boundary conditions. Based on the obtained temperature profile, a thermal stabilization time is defined and used to estimate the appropriate delay between successive layer depositions. The results indicate that the deposited filament reaches near-ambient thermal conditions within approximately 20 seconds for the selected process parameters. This estimated delay provides a simple and practical guideline for improving inter-layer bonding and reducing thermally induced defects. The proposed approach enables the conversion of thermal simulation results into actionable process planning inputs and can be integrated with slicing strategies for enhanced FDM part quality.

Keywords: FDM, fused filament fabrication, finite element analysis, FEA

1. Introduction

Fused deposition modeling (FDM) is one of the most widely used additive manufacturing techniques due to its simplicity, cost-effectiveness, and ability to fabricate complex polymer components. In this process, a thermoplastic filament is extruded through a heated nozzle and deposited layer by layer to form a three-dimensional part. The quality and mechanical performance of FDM-fabricated parts are strongly influenced by process parameters, particularly the thermal history during deposition. During the

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FDM process, the extruded filament undergoes rapid cooling and solidification, which governs inter-layer bonding and structural integrity. Previous studies have shown that temperature evolution significantly affects bonding strength, residual stresses, and dimensional accuracy of printed parts (Sun et al., 2008, Alafaghani et al., 2017, Li et al., 2002). Improper thermal control often results in defects such as warping, delamination, and poor surface finish. To better understand these effects, several researchers have employed numerical approaches, including finite element analysis, to model the transient thermal behavior of FDM. Techniques such as element birth and death have been used to simulate the sequential deposition of material and capture heat transfer between adjacent filaments (Casavola et al., 2017, Costa et al., 2015, Kumar & Regalla, 2011). These studies primarily focus on predicting temperature distribution and understanding heat transfer mechanisms. However, despite these advancements, limited work has been directed toward translating thermal analysis results into practical process guidelines. In particular, the selection of inter-layer deposition delay is often based on empirical judgment rather than quantitative analysis. This gap highlights the need for a simple and effective method to estimate the appropriate delay between successive layer depositions based on thermal behavior (Mahapatra et al., 2006, Armentani et al., 2007, Ji & Zhou, 2010, Wang et al., 2012, Tong et al., 2014, Zhang & Chou, 2006, Compton et al., 2017).

In the present study, a transient thermal model is developed using the element birth–death technique to simulate the deposition of an ABS filament. Based on the obtained temperature evolution, a thermal stabilization time is defined and used to estimate the inter-layer deposition delay. This approach provides a practical guideline for process planning, enabling improved control over thermal gradients and enhanced quality of FDM-fabricated parts.

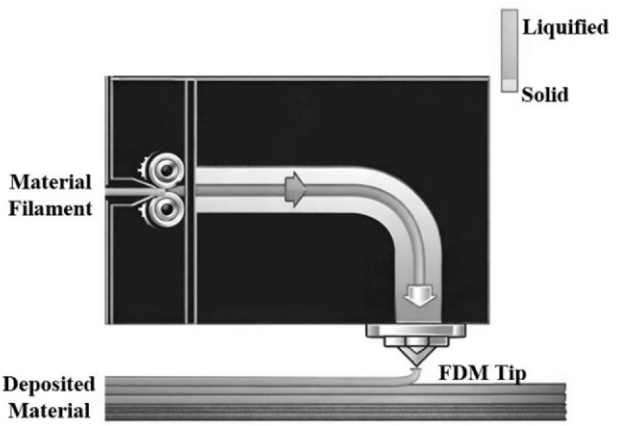


Figure 1. Schematic diagram of fused deposition modeling process (Sun, Q et al., 2008)

2. Methodologies

In the present study, a transient thermal model is developed to simulate the cooling behavior of a deposited filament during the fused deposition modeling (FDM) process. The methodology combines finite element analysis with a sequential element activation approach to represent the layer-wise material deposition.

2.1 Material Selection and Properties

Acrylonitrile Butadiene Styrene (ABS) is selected as the build material due to its widespread use in FDM and its sensitivity to thermal effects such as warping and shrinkage. The thermo-physical properties of ABS used in the simulation, including thermal conductivity and specific heat, are adopted from standard literature and are summarized in Table 1.

Table 1. Material Properties of ABS Material (Zhang, Y. et al., 2006)

Properties	Value	Properties	Value
Specific heats (KJ//Kg K)		**Enthalpy (KJ//Kg K)**	
At 273 K	1.62	At 273 K	0
At 378 K	1.62	At 378 K	109
At 403 K	3	At 403 K	153
At 553 K	1.68	At 553 K	308
Conductivity (W/m K)		0.19	

2.2 Geometrical Modeling

The deposited filament is modeled as a single-layer structure to isolate and study the fundamental thermal behavior without introducing multi-layer complexity. The filament is represented as a rectangular geometry with a length of 80 mm and a width of 0.5 mm, corresponding to typical FDM nozzle dimensions. To simplify the analysis and focus on primary heat transfer mechanisms, the following assumptions are made (these assumptions allow for efficient modeling while capturing the dominant thermal behavior of the process):

- Heat transfer is predominantly one-dimensional along the filament length due to a high length-to-width ratio.
- Heat loss occurs mainly through natural convection to the surrounding environment.
- Heat conduction through the build platform is neglected. Material properties are considered temperature-dependent where applicable.

2.3 Finite Element Modeling

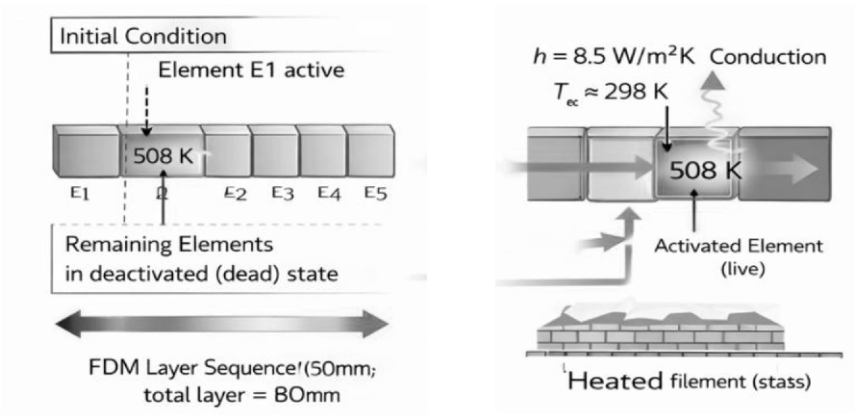


Figure 2. (a) Initial Condition and Element Activation (b) Boundary Condition for Activated Element

The thermal analysis is performed using ANSYS APDL. The filament geometry is discretized into a series of finite elements along the deposition path. Initially, all elements are deactivated (dead state), and elements are progressively activated (live state) to simulate the sequential deposition of material. When an element is activated, it is assigned an initial temperature corresponding to the extrusion temperature.

Heat transfer then occurs through conduction between adjacent active elements and through convection to the surrounding environment. The convection heat transfer coefficient is taken as 8.5 W/m²K, and the ambient temperature is assumed to be 298 K. This element birth–death technique enables the realistic simulation of the layer-by-layer deposition process and captures the transient thermal interactions between deposited segments.

Figure 2 illustrates the finite element modeling strategy adopted in the present study to simulate the filament deposition process in fused deposition modeling using the element birth and death technique. As shown in Figure 2 (a), the deposited filament layer is discretized into a series of finite elements along the deposition direction.

2.4 Thermal Stabilization Criterion

To quantify the cooling behavior of the deposited filament, a thermal stabilization criterion is introduced. The temperature difference between the filament and ambient condition is defined as:

$$\Delta T = |T - T_ambient| \quad \ldots (1)$$

The filament is considered thermally stable when the temperature difference falls within a small tolerance range, defined as:

$$\Delta T \leq 5 \text{ K} \quad \ldots (2)$$

The time required to satisfy this condition is defined as the thermal stabilization time (t_s). This parameter is used as a basis for estimating the inter-layer deposition delay.

2.5 Estimation of Inter-Layer Deposition Delay

Based on the transient thermal analysis, the cooling curve of the deposited filament is obtained. The thermal stabilization time (t_s) is extracted from this curve and is used to estimate the minimum delay required before depositing the subsequent layer. This estimated delay serves as a practical guideline for process planning in FDM, enabling better control of thermal gradients and improved inter-layer bonding.

3. Results and Discussion

The transient thermal behavior of the deposited filament during the fused deposition modeling (FDM) process was analyzed using the developed finite element model based on the element birth–death technique. The focus of this analysis is to understand the temperature evolution during sequential deposition and to estimate the thermal stabilization time for process planning. The temperature distribution of individual filament elements at their corresponding end nodes is presented in Table 2. It can be observed that the initially deposited elements exhibit higher temperature values due to their longer exposure to heat accumulation, whereas the later-deposited elements approach ambient temperature more rapidly. Specifically, the temperature values gradually decrease along the deposition sequence, indicating progressive cooling and stabilization of the filament. This trend further validates the transient cooling behavior captured by the model and supports the estimation of thermal stabilization time.

3.1 Temperature Evolution During Deposition

When the first filament element is activated, it is initialized at the extrusion temperature and undergoes rapid cooling due to heat loss to the surrounding environment.

At this stage, since no neighboring elements are active, the heat transfer is dominated by convection, resulting in a steep temperature gradient. As subsequent elements are activated, heat transfer occurs not only through convection but also through conduction between adjacent filament segments. This interaction leads to a thermal inheritance effect, where newly deposited elements experience a relatively slower cooling rate due to the residual heat of previously deposited material. This behavior highlights the

importance of considering sequential deposition in thermal modeling of FDM.

3.2 Cooling Behavior and Thermal Stabilization

The cooling profile of the deposited filament indicates a rapid decrease in temperature immediately after deposition, followed by a gradual approach toward ambient conditions. It is observed that a significant portion of the temperature drop occurs within the initial 10–15 seconds, after which the rate of cooling reduces substantially. Using the defined thermal stabilization criterion, the filament is considered to have reached near-ambient conditions when the temperature difference falls within the specified tolerance. Based on this criterion, the thermal stabilization time (t_s) for the deposited filament layer is estimated to be approximately 20 seconds under the given process conditions.

This result indicates that the thermal behavior of FDM is highly transient and that sufficient time is required for the deposited material to dissipate heat before the addition of subsequent layers.

3.3 Implications for Inter-Layer Deposition Timing

The estimated thermal stabilization time provides a practical basis for determining the delay between successive layer depositions. If the next layer is deposited before sufficient cooling of the previous layer, excessive thermal gradients may develop, leading to defects such as warping, residual stresses, and dimensional inaccuracies. On the other hand, excessive delay may result in inadequate inter-layer bonding due to reduced thermal diffusion between layers. Therefore, the identified stabilization time represents a balanced condition that can help optimize both bonding quality and dimensional stability.

Table 2. The temperature of each element at the at end node

Elements	Corresponding end nodes		Temperature in Kelvin
E1	22	3	385
E2	21	4	335
E3	20	5	314
E4	19	6	305
E5	18	7	302
E6	17	8	300
E7	16	9	300
E8	15	10	300
E9	14	11	300
E10	13	12	300

3.4 Practical Interpretation for Process Planning

The findings of this study can be directly applied in FDM process planning. The estimated delay of approximately 20 seconds can be incorporated into printing strategies through controlled pauses between layers. This can be implemented either by modifying G-code instructions or by adjusting cooling-related parameters in slicing software. Although the exact value of the delay may vary depending on material properties and environmental conditions, the proposed approach provides a systematic method to estimate inter-layer deposition timing based on thermal behavior rather than empirical assumptions.

3.5 Discussion and Comparison with Existing Understanding

Unlike conventional thermal studies that primarily focus on predicting temperature distribution, the present work extends the analysis by linking thermal behavior with process decision-making. The

introduction of a thermal stabilization time as a guiding parameter enhances the practical applicability of the model. The results confirm that the sequential nature of deposition significantly influences cooling behavior and must be considered when analyzing heat transfer in FDM. The element birth–death technique effectively captures this phenomenon and provides a reliable approach for studying transient thermal effects in layer-wise manufacturing processes.

4. Conclusion

In the present study, a transient thermal model based on the element birth–death technique was developed to investigate the cooling behavior of a deposited filament in the fused deposition modeling (FDM) process. The model successfully captures the sequential nature of material deposition and the associated heat transfer through convection and conduction between adjacent filament elements. The analysis revealed that the deposited filament undergoes rapid cooling immediately after extrusion, followed by a gradual approach toward ambient temperature. Based on the defined thermal stabilization criterion, the stabilization time for the considered process conditions was estimated to be approximately 20 seconds. The temperature distribution presented in Table 2 further supports the progressive cooling behavior along the deposition sequence. A key contribution of this study is the estimation of inter-layer deposition delay based on thermal behavior. The identified stabilization time provides a simple and practical guideline for selecting the delay between successive layer depositions, which can help in reducing thermal gradients, minimizing defects such as warping, and improving inter-layer bonding. The proposed approach transforms conventional thermal analysis into a useful tool for process planning in FDM. The estimated delay can be incorporated into printing strategies through G-code modification or slicing parameter adjustment. Although the results are based on specific material and process conditions, the methodology can be extended to other materials and printing environments.

The key contributions of this study are as follows:

1. Definition of a thermal stabilization criterion ($\Delta T \leq 5$ K) and corresponding stabilization time (t_s) as a measurable process parameter, enabling quantitative assessment of cooling behavior in FDM.
2. Estimation of an optimal inter-layer deposition delay (~20 seconds for ABS under given conditions) derived directly from transient thermal analysis, providing a clear and actionable process guideline.
3. Transformation of thermal simulation results into a decision rule for process planning, replacing empirical selection of deposition timing with a physics-based approach.
4. Demonstration of the relationship between deposition timing and defect formation (warping, residual stress, and bonding quality) through thermal behavior analysis.
5. Provision of a directly implementable strategy for FDM systems via G-code modification or slicer parameter tuning, enabling practical adoption without additional hardware.

Future work may include multi-layer modeling, incorporation of build platform conduction, and experimental validation to further enhance the accuracy and applicability of the proposed approach.

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