

Temperature Modeling for Laser-based Directed Energy Deposition Process

by

Zhaolin Wei

B.Sc., The University of Macau, 2024

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

in

The Faculty of Applied Science

(Mechatronics Design)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

August 2025

© Zhaolin Wei 2025

Abstract

Laser metal additive manufacturing technology is an advanced manufacturing technology developed based on laser cladding technology. This technology facilitates the expeditious fabrication and re-manufacturing of intricate metal components. During the laser additive manufacturing process, the stability of the melt pool temperature exerts a direct influence on the dimensional accuracy, metallurgical defects, solidification structure, and mechanical properties of the formed parts. Consequently, it is imperative to continuously monitor the melt pool temperature and implement closed-loop control to ensure a stable temperature, thereby enhancing the quality of the formed product. However, due to the intricacy of the melt pool temperature mechanism model (which necessitates extended computation times, impeding the acquisition of results within a single control cycle) and the constraints imposed by PID control algorithms (which complicate the management of multiple variable constraints demanded by the control system), there is presently a paucity of closed-loop control algorithms that are applicable to melt pool temperature and cooling rate in laser additive manufacturing. This study systematically investigates the aforementioned issues, utilizes validated finite element simulations to collect data, fits state space equations, and verifies these equations through specific experiments, thereby attaining ideal results.

Table of Contents

Abstract ii

Table of Contents iii

List of Tables vi

List of Figures vii

Glossary ix

List of Symbols x

Acknowledgements xi

Dedication xii

1 Introduction 1

 1.1 Introduction of Metal Additive Manufacturing 1

 1.2 Scope of the Project 2

2 LDED Heat Transfer Analysis and Finite Element Model 4

 2.1 Theoretical Basis of Temperature Field Simulation 4

 2.1.1 Laser Heat Source 5

 2.1.2 Heat Conduction 5

 2.1.3 Boundary Conditions 6

2.1.4	Phase Transformation and Latent Heat	6
2.2	Material Parameters	7
2.3	Geometric Model for Laser Additive Manufacturing Process Simulation	8
3	Analysis of Input Parameters on Temperature Field	9
3.1	Characteristics of Temperature Field	9
3.1.1	Analysis of Thermal Cycling Results	10
3.1.2	Influence of Process Parameters on Pre-scan Temperature	11
3.2	Approaches to Finite Element Modelling for Different Printing Materials and Parameters	11
4	Establishment and Validation of the State-Space Model	13
4.1	Proposal of Discrete Temperature Prediction Model	13
4.1.1	Cooling Time for Unidirectional Printing	15
4.1.2	Cooling Time for Bidirectional Printing	15
4.2	Refinement and Validation of State Equations with Experimental Data	16
4.2.1	State Equation Adaptation for FE Model	16
4.2.2	State Equation Adaptation for Experiment Data	18
4.3	Modelling of Liquid-Solid Solidification Cooling Rates	20
4.3.1	Analysis of Factors Influencing Solidification Cooling Rates	21
5	Conclusion	23
5.1	Summary	23
5.2	Limitation and Analysis	23
5.3	Future Work	24
	Bibliography	25

Appendices

A Supplement Figures	27
B Linearization Process	31
B.1 Linearization Procedure	31
B.2 Controllability Analysis	32
C Cooling Rate Calculation	34
D Closed-loop Control Scheme	35
E FE Model Simulation Data	37

List of Tables

2.1	The compositions of Ti6Al4V [12]	7
2.2	The physical and mechanical parameters of Ti6Al4V [12]	8
2.3	Thermophysical properties of Ti6Al4V at different temperatures [12]	8
4.1	Statistical result of state	17
4.2	Chemical composition of 316 stainless steel powder and substrate material (wt%) . . .	18
4.3	Experimental Trials	18
4.4	Performance Metrics	20
E.1	Temperature Data of Simulation Results.	37
E.2	Solidification Cooling Rate Collected by FE model.	56

List of Figures

1.1	Schematic of the LDED Process	2
1.2	Unified Modeling Workflow for Different Materials and Processing Methods	3
2.1	Schematic Diagram of the Heat Transfer Process in LDED	4
3.1	Comparison Data from FE Model with Literature Data	9
3.2	Temperature Distribution Map at Different Times	10
3.3	Tracking the Temperature of Each Layer Midpoint over Simulation Time	10
3.4	Effects of Different Process Parameters on the Temperature of the Bottom Center of Each Layer in the Experiment (Laser power, scanning speed, and dwell time)	11
3.5	Validation of FE Model with Experiment Data	12
4.1	Effect of Energy Density on the Maximum Temperature of Each Layer by Simulation .	13
4.2	Initial Temperature Distribution for Different Printing Types by Simulation	14
4.3	Simplified Layer Demonstration	15
4.4	Temperature prediction results for $T_{init,M,k}$ in unidirectional printing using model 4.12 with constant λ and α	17
4.5	Temperature prediction results for $T_{init,L,k}$ in unidirectional printing using model 4.12 with constant λ and α	18
4.6	Recursive Simulation Comparison between Model (Eq 4.12) and Model (Eq 4.13) Using Training Set Results from Experiment Trial 1–4.	19
4.7	Recursive Simulation Comparison between Model (Eq 4.12) and Model (Eq 4.13) Using Test Set Results from Experiment Trial 5–6.	20

4.8	3D Relationship between Cooling Rate and Scanning Speed, Initial Temperature and Power	21
4.9	3D fitting results between cooling rate and scanning speed, initial temperature and power	22
5.1	Temperature prediction results for $T_{init,L,k}$ and $T_{init,R,k}$ in bidirectional printing using model 4.12 with printing interval equals 10s.	23
A.1	Temperature prediction results for $T_{init,L,k}$ in bidirectional printing model 4.12 with constant λ and α	27
A.2	Temperature prediction results for $T_{init,M,k}$ in bidirectional printing model 4.12 with constant λ and α	28
A.3	Temperature prediction results for $T_{init,R,k}$ in bidirectional printing model 4.12 with constant λ and α	28
A.4	Temperature prediction results for $T_{init,R,k}$ in unidirectional printing model 4.12 with constant λ and α	29
A.5	Experimental setup showing the main components: (a) Head and Substrate, (b) IR Camera Set up (c) Temperature data acquisition system for signal processing and measurement recording	30
D.1	RS232 Serial Communication Protocol	35
D.2	Information Received by dSPACE Serial Port from Colorimetric Thermometer	36
D.3	Simulink Control Strategy for Prototyping Experiments	36

Glossary

AM: Additive Manufacturing

CAD: Computer-Aided Design

CR: Cooling Rate

DED: Directed Energy Deposition

EBM: Electron Beam Melting

EBS**D:** Electron Backscatter Diffraction

FE: Finite Element

HAZ: Heat-Affected Zone

LDED: Laser Directed Energy Deposition

LMD: Laser Metal Deposition

LPBF: Laser Powder Bed Fusion

LQR: Linear-Quadratic Regulator

MIMO: Multiple-Input Multiple-Output

PBF: Powder Bed Fusion

PID: Proportional-Integral-Derivative

SEM: Scanning Electron Microscope

SISO: Single-Input Single-Output

SLM: Selective Laser Melting

SS: State-Space

UTS: Ultimate Tensile Strength

List of Symbols

Symbol	Description
T	Temperature
$T_{m,k}$	Prescan temperature of the middle segment at k^{th} layer
$T_{ambient}$	Ambient or initial temperature
ρ	Density
c_p	Specific heat capacity
k	Thermal conductivity
η	Laser absorptivity coefficient
ε	Emissivity
P	Laser power
v	Laser scan speed
h	Hatch spacing
t	Layer thickness
E	Volumetric energy density
D	Laser beam diameter
$\mathbf{x}$	State vector
$\mathbf{u}$	Input vector
$\mathbf{y}$	Output vector
A	State matrix
B	Input matrix
C	Output matrix
D	Feed-forward matrix
K	Feedback gain matrix (e.g., for LQR)
x, y, z	Cartesian coordinates
t	Time
τ	Dwell time
Δt	Total interval before printing next layer

Acknowledgements

I'm so grateful to Professors Ryoze Nagamune and Xiaoliang Jin for their careful guidance throughout this process. During my master's studies, they were so helpful and taught me so much, and I'm so grateful for all they did for me.

I would like to express my gratitude to Kezi Li, Zahra, Jacqueline Tang, and Zhiyuan Wang. The discussions within the research group broadened my horizons and provided invaluable assistance in successfully completing my master's thesis.

Dedication

Dedicated to my family and my friends for their constant support. Also, Qianya, for your love.

Chapter 1

Introduction

1.1 Introduction of Metal Additive Manufacturing

Additive manufacturing technology, also known as 3D printing technology, has emerged as a pivotal technology in the domains of scientific and technological development, as well as commercial production [6]. The additive manufacturing process utilizes computer-aided design (CAD) for graphics, printing, and scanning, layer by layer, according to computer programming. A Comparison of AM with traditional production technologies reveals that AM does not necessitate pre-processing or the use of fixed moulds. This approach has been demonstrated to reduce production cycle time, enhance labour productivity, and decrease component production [1].

Representative processes in additive manufacturing include powder-fed directed energy deposition (DED) and powder bed fusion (PBF), both of which are based on powder [5]. These technologies enable the direct production of functional parts, whose quality can rival that of parts manufactured using traditional processes while eliminating many post-processing steps. Syed et al., from the University of Manchester [11] conducted a comparative analysis of the process characteristics and advantages and disadvantages of wire-fed and powder-fed direct laser deposition technologies. The study revealed that samples deposited using both methods exhibited adequate surface finish on the top surface and side walls, with analogous microstructures.

Laser Directed Energy Deposition (LDED) is a process method that uses a laser as the primary heat source based on its underlying principles. In the LDED process, the processing platform remains stationary, while the feeding system and laser simultaneously follow the scanning path and additive height. The scanning speed of the laser is generally slower, primarily constrained by the efficiency of powder and wire entering the melt pool. Before the initiation of each processing cycle, a uniform layer of powder is dispensed across the powder bed. Concurrently, the laser beam traverses the scanning path in the horizontal direction, thereby facilitating the attainment of remarkably elevated scanning speeds during the processing process.

Figure 1.1 illustrates the Laser Direct Energy Deposition (LDED) process. It features a coaxial nozzle that directs a laser beam onto a substrate. Metal powder, combined with a powder feeding gas, is introduced alongside the laser. The shielding gas protects the melt pool, which forms as the laser melts the metal powder, resulting in a deposited layer on the substrate.

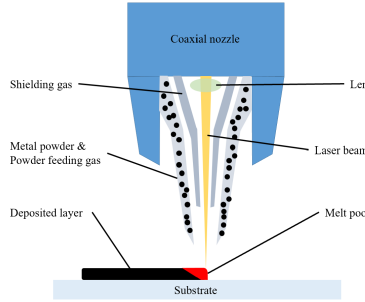


Figure 1.1: Schematic of the LDED Process

Ti6Al4V is a widely utilized material in the field of LDED. This material is distinguished by its high specific strength, excellent corrosion resistance, and a range of mechanical and thermochemical properties [10]. However, due to the necessity of forming powder layers during the LDED process, characterized by relatively thin layer thicknesses and small laser spot diameters, the process efficiency remains comparatively low. Furthermore, the formation process must be carried out in an environment filled with a protective gas; argon gas is used in this particular experiment. Work by Baufeld et al. [3] on wire-fed Ti6Al4V components reported ultimate tensile strength (UTS) values between 900–1014 MPa. They also observed significant anisotropy in ductility, with strain-to-failure being much higher in the build direction (up to 16.4%) than in directions parallel to the deposition layers (approx. 9%).

1.2 Scope of the Project

Presently, the majority of methods for controlling melt pool temperature are based on enhanced PID algorithms [4]. The structural simplicity and ease of design of such control algorithms are noteworthy. In the domain of laser additive manufacturing, it is imperative to impose numerous constraints on system variables. However, the utilization of PID control algorithms in this context presents a challenge, as these algorithms are not designed to accommodate multiple constraints within the controller. When hard constraints are set using PID algorithms, environmental noise and disturbances can cause significant system oscillations, leading to abnormal processing operations. The LDED process is a physical metallurgical process that involves the interaction of a laser, metal powder, substrate, and protective gas. The process is intricate, which complicates the establishment of an accurate mechanistic model of melt pool temperature during the process.

The state-space method can depict the internal state of the system and intervene in all states of the system, provided the system state is observable or measurable. It is well-suited for designing MIMO (multiple-input, multiple-output) systems using controllers. Consequently, this study employs a discrete state-space equation to describe the LDED process, thereby enabling the application of

control theory within the production process. In the domain of laser additive manufacturing, the cooling rate during metal solidification exerts a pivotal influence on the microstructure of the metal. Consequently, the stability of the cooling rate emerges as a crucial indicator of process stability.

Figure 1.2 illustrates the range of research methods employed in this study. It begins with the collection of experimental data related to material properties and processing parameters, forming the foundation for the analysis. The process involves developing a finite element model that incorporates essential material properties and boundary conditions. Following this, data processing is conducted to establish state-space equations, which are crucial for accurate simulation. Additionally, there is a focus on optimizing the process scheme to enhance the effectiveness of the forming process. A key component of the analysis is the examination of the molten pool, particularly with process parameters and printing height. Finally, the results are summarized, highlighting findings related to pool size and temperature. This structured approach significantly improves the understanding of thermal behavior during LDED, facilitating better control over the deposition process. This paper mainly focuses on the content of the first part.

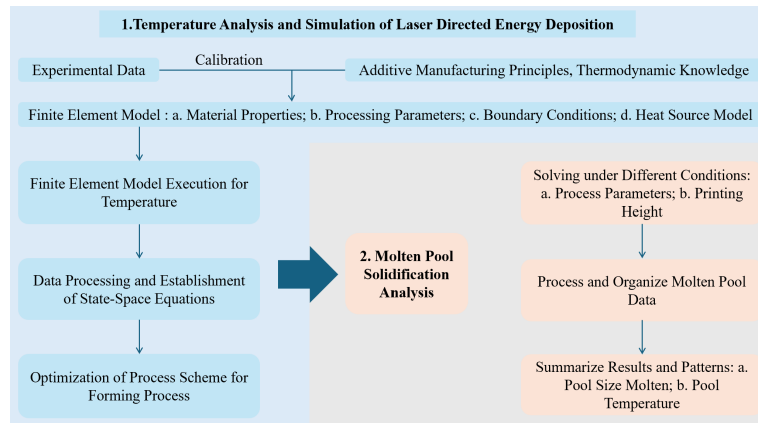


Figure 1.2: Unified Modeling Workflow for Different Materials and Processing Methods

Chapter 2

LDED Heat Transfer Analysis and Finite Element Model

Finite element software simulation is increasingly recognized as a more effective, convenient, and cost-efficient research method in 3D printing [2]. In comparison with conventional experimentation, the implementation of finite element software simulation has been demonstrated to enhance additive manufacturing capacity and reduce the material and product development cycle. Additionally, it facilitates the prediction and correction of product defects. Consequently, in the subsequent evolution of 3D metal printing technology, the function of finite element numerical simulation is paramount. In this report, the MATLAB is employed for the numerical simulation of two-dimensional metal heat conduction analysis.

2.1 Theoretical Basis of Temperature Field Simulation

As the laser beam traverses the powder bed surface, the metal powder absorbs heat, melts into a liquid, releases heat, cools, solidifies, and fuses with the substrate. During this process, phenomena such as heat conduction, convection, and radiation occur, and the thermal properties of the metal alloy material undergo corresponding changes.

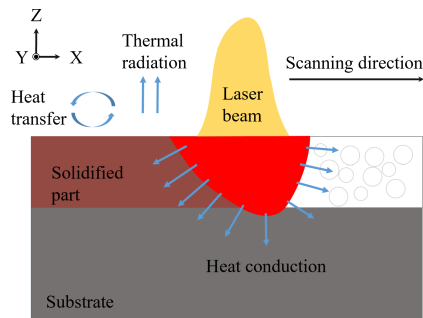


Figure 2.1: Schematic Diagram of the Heat Transfer Process in LDED

Figure 2.1 illustrates the heat transfer process involved in LDED. After the metal powder is melted by the laser, heat is transferred to the lower layer through conduction and ultimately to the substrate.

It is imperative to note that all surfaces in contact with air undergo a process of heat dissipation to the environment through convection and radiation.

2.1.1 Laser Heat Source

The laser heat source model is a mathematical representation of the thermal energy properties of laser melting. The temperature field distribution characteristics defined by this model primarily drive the melting of powdered materials by lasers. The accuracy of the heat source model influences the temperature field distribution during the additive manufacturing process. There are currently several commonly used types of moving heat source models, including the Gaussian, Semi-Ellipsoidal, and others. This model employs a volumetric Gaussian heat source, which accurately describes the spatial decay of the laser beam's energy:

$$\dot{Q}(r) = \frac{A \cdot P}{\pi r_b^2 h} \exp\left(-\frac{Dr^2}{r_b^2}\right) \quad (2.1)$$

where $\dot{Q}(r)$ is the heat source density at a distance r from the laser center (W/mm^3), A is the effective energy absorptivity defined as $A = (\eta_p + (1 - \eta_p)\eta_l) \cdot \eta_{\text{power}}$, η_p is the energy absorption coefficient of the powder in flight, η_l is the absorption coefficient of the deposited layer, P is the laser power (W), D is the laser beam intensity distribution factor (dimensionless), r_b is the characteristic radius of the laser beam (mm), h is the single layer thickness (mm), and r is the radial distance from the laser center (mm).

2.1.2 Heat Conduction

DED processing is an instantaneous heat transfer process. The non-linear transient heat conduction equation describes the heat transfer phenomena in the metal additive manufacturing process:

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \nabla \cdot [k(T)\nabla T] + \dot{q}(x, y, z, t) \quad (2.2)$$

where $\rho(T)$ is the material density (g/mm^3), $C_p(T)$ is the temperature-dependent specific heat capacity ($\text{J}/\text{g}\cdot\text{K}$), $k(T)$ is the temperature-dependent thermal conductivity ($\text{W}/\text{mm}\cdot\text{K}$), T is the temperature field (K), t is time (s), and $\dot{q}(x, y, z, t)$ is the volumetric heat source term (W/mm^3).

Heat conduction in the laser additive manufacturing process involves heat transfer between the additive part and the substrate, the laser melt pool and solidified material, unmelted and melted powder, and the solidified region.

2.1.3 Boundary Conditions

When $t = 0$, assuming that the powder and substrate are at the same temperature, both at room temperature, the initial conditions are:

$$T(x, z, t)|_{t=0} = 296.15K \quad (2.3)$$

Except for the bottom surface, heat transfer on each surface can be expressed as:

$$-k\left(\frac{\partial T}{\partial z}\right) = \varepsilon\sigma(T^4 - T_a^4) + h(T - T_a) \quad (2.4)$$

where ε is the thermal radiation coefficient of the material surface, σ is the Stefan-Boltzmann constant for thermal radiation.

The energy lost from the outer surface of the additive sample and substrate to the surrounding environment through air convection is:

$$\dot{q}_{convection} = h(T - T_{ambient}) \quad (2.5)$$

In the equation, h is the convective heat transfer coefficient, taken as $h = 60 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$, and T is the temperature of the material surface. In the laser additive manufacturing process, the materials are in an environment of inert protective gas, where they undergo thermal convection with the gas. At the same time, the materials have a high initial temperature due to the intense irradiation of the laser light source. Therefore, a significant proportion of heat transfer occurs through thermal convection. However, since the different sides of additive manufacturing parts have varying degrees of convection with the inert gas, different heat exchange parameters must be set on their surfaces to ensure the accuracy of the simulation process.

Radiative heat transfer follows the Stefan-Boltzmann law:

$$\dot{q}_{radiation} = \varepsilon\sigma(T^4 - T_{ambient}^4) \quad (2.6)$$

where $\dot{q}_{radiation}$ is the radiative heat flux (W/mm^2), ε is the material surface emissivity, and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-14} \text{ W}/\text{mm}^2 \cdot \text{K}^4$). In the laser additive manufacturing process, heat transfer is primarily achieved through heat exchange and conduction. Heat radiation has a relatively minor impact on the temperature field.

2.1.4 Phase Transformation and Latent Heat

Latent heat of phase change refers to the heat absorbed and released by a material during solidification as it undergoes a phase change. In LDED, metal powder is melted by the laser beam, and part of

the metal in the previous additive layer is also remelted. The resulting melt pool continuously moves as the laser moves away, causing a fixed point on the additive layer to undergo a transformation from the solid phase to the liquid phase and back to the solid phase. Therefore, the phase change type generated in the laser additive manufacturing process is a solid-liquid phase change that first absorbs heat and then releases heat.

The solid-liquid phase transformation during cooling is a key process governing microstructure formation. This model employs the effective specific heat capacity method to handle the latent heat of fusion, distributing it over the temperature range between the solidus (T_s) and liquidus (T_l) temperatures:

$$C_{p,\text{eff}}(T) = C_p(T) + \frac{L}{T_l - T_s} \quad \text{for } T_s \leq T \leq T_l \quad (2.7)$$

where $C_{p,\text{eff}}(T)$ is the effective specific heat capacity (J/g·K), L is the latent heat of fusion (J/g).

2.2 Material Parameters

The simulation focus of this study is the Ti6Al4V alloy material. Its notable advantages include good heat resistance, high strength, good plasticity, strong toughness, good formability, good weldability, and good corrosion resistance [9], making it widely used in the aerospace and biopharmaceutical fields. The primary chemical composition of Ti6Al4V is presented in Table 2.1.

Table 2.1: The compositions of Ti6Al4V [12]

Element	Ti	Al	V
Weight %	87.9	7.4	4.7
Atomic %	83.3	12.5	4.2

To reduce computational complexity, the following assumptions were made for the model:

1. The Ti6Al4V alloy was assumed to be an isotropic, homogeneous material.
2. The laser absorption rate of Ti6Al4V is constant.
3. Material evaporation was not considered during the laser additive manufacturing process (the evaporation temperature of Ti6Al4V is approximately 3315 K).
4. Process parameters, such as the powder feed rate, laser defocusing, and the carrier gas flow rate, are not considered to affect the manufacturing process.
5. The bottom surface of the substrate is in an adiabatic state.

Table 2.2: The physical and mechanical parameters of Ti6Al4V [12]

Material Property	Value
Solid density (kg/m ³)	4428
Powder density (kg/m ³)	2214
Poisson's ratio	0.41
Melting point (°C)	1655
Evaporation point (°C)	2976
Solidus temperature (°C)	1605
Liquidus temperature (°C)	1655
Latent heat (J/kg)	365000

The finite element analysis process for laser additive manufacturing of Ti6Al4V alloy is a nonlinear transient analysis, in which material properties vary with temperature, as shown in Table 2.3. As the temperature rises, the density of the material decreases slightly, while thermal conductivity, specific heat, and enthalpy all show a clear upward trend.

Table 2.3: Thermophysical properties of Ti6Al4V at different temperatures [12]

Property \ Temp (°C)	25	300	700	995	1300	1650	1650 [†]	1700
Density ρ (kg/m ³)	4420	4381	4324	4282	4240	4189	3920	3886
Thermal Conductivity k (W/m·K)	7.0	10.2	15.5	22.7	23.7	28.4	33.4	34.6
Specific Heat c_p (J/kg·K)	546	606	694	753	696	759	831	840
Enthalpy ΔH (J/g)	0	158	419	636	885	1184	1466	1508

2.3 Geometric Model for Laser Additive Manufacturing Process Simulation

The thickness of the powder layer in the laser melting process is frequently less than one millimeter. The dimensions of the grid cells must be reduced to a scale that is smaller than the thickness of the powder layer. Furthermore, the laser melting process necessitates a time for heat dissipation. Consequently, the geometric model size in the finite element simulation of laser melting should not be set too small to avoid the geometric model size effect on the temperature field and melt pool shape. In this simulation, a 0.3 mm rectangular cell was used for mesh partitioning, with a total of 10 printed layers. The scan trajectory length is 150 millimeters, the substrate thickness is 15 millimeters, and the remaining inactive grid cells are reserved for subsequent additive layers. The total number of grid cells in the entire model is 31,500. The division of grid cells should correspond to the analysis steps and related secondary development settings.

Chapter 3

Analysis of Input Parameters on Temperature Field

A thermal finite element analysis was conducted on the laser additive manufacturing process for multi-layer, thin-walled Ti6Al4V alloy components to study the temperature field and evolution mechanisms. The accuracy of the finite element model is crucial for obtaining accurate data. Before collecting data, a comparison of the model data with real-world data is necessary. As illustrated in Figure 3.1, the FE model has been shown to accurately predict the pre-scan temperature for each processing cycle, as evidenced by its alignment with experimental data obtained by J.C. Heigel et al [7].

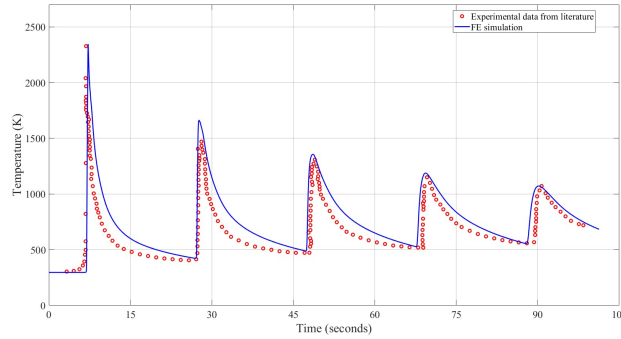


Figure 3.1: Comparison Data from FE Model with Literature Data

3.1 Characteristics of Temperature Field

Figure 3.2 presents the temperature distribution at different time intervals during laser additive manufacturing of thin-walled components using the FE model. The red line marks the melting point boundary of Ti6Al4V. Simulation with a Gaussian heat source shows that the laser forms a melt pool and a circular spot on the surface. At the same time, the surrounding temperature exhibits a comet-shaped distribution with steeper gradients near the center and at the front of the spot. In the first layer, the melt pool height is sufficient, and the morphology is stable. However, at later stages, excessive thermal input causes severe heat accumulation, which in practice may result in remelting

or collapse.

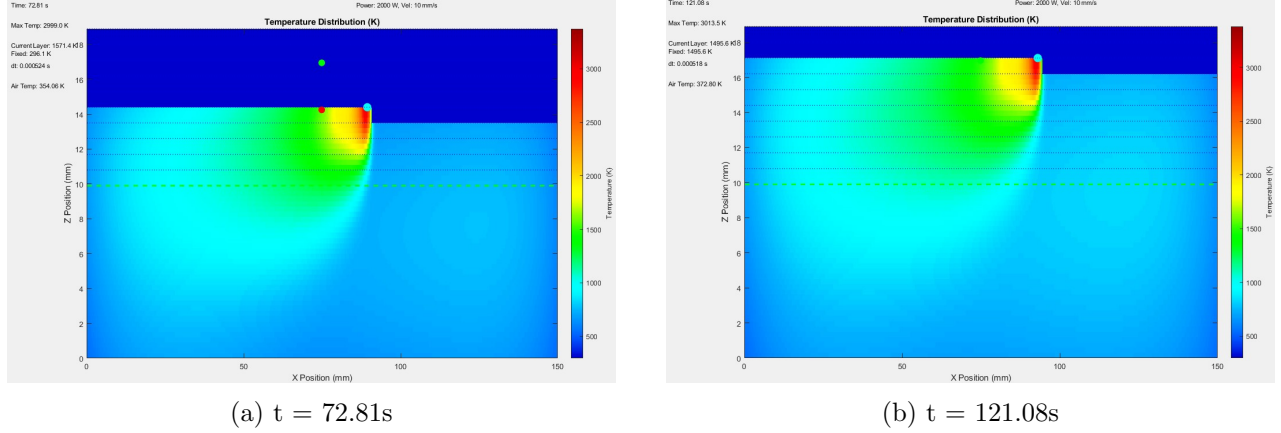


Figure 3.2: Temperature Distribution Map at Different Times

3.1.1 Analysis of Thermal Cycling Results

The FE model results in Figure 3.3 show that midpoint temperatures rise sharply as the laser passes and quickly decline afterward due to the limited spot size. Subsequent layers affect lower nodes through the heat-affected zone, causing repeated temperature fluctuations with decreasing amplitude and delayed peaks as layers increase. Thermal accumulation leads to higher peak temperatures in successive layers, with the second layer already exceeding the first.

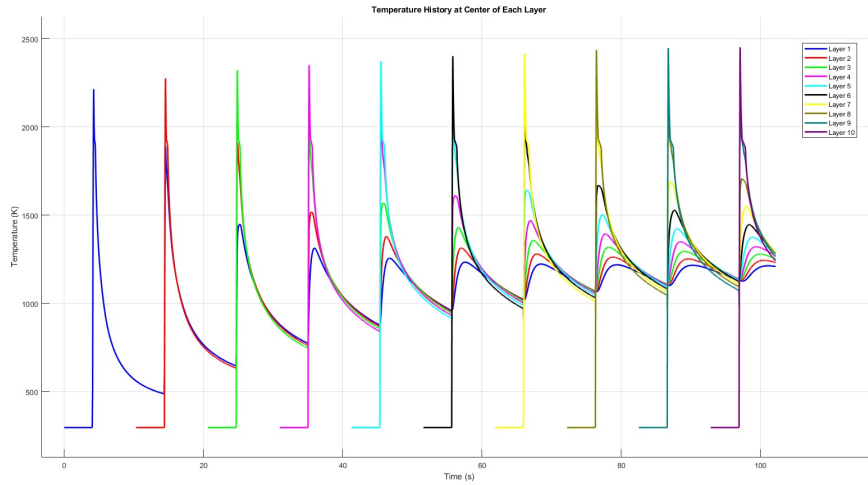


Figure 3.3: Tracking the Temperature of Each Layer Midpoint over Simulation Time

3.1.2 Influence of Process Parameters on Pre-scan Temperature

Significant thermal accumulation occurs in thin-walled components due to interlayer environmental changes and process parameter limits. The pre-scan temperature of each layer significantly impacts specimen accuracy, stress distribution, microstructure, and product quality, making its control crucial.

To examine parameter effects on thermal behavior, experiments varied laser power, scanning speed, interlayer interval, and preheating temperature. As shown in Figure 3.4 (parameters in Table 4.3), pre-scan temperatures at the layer tops increase with both laser power and scanning speed.

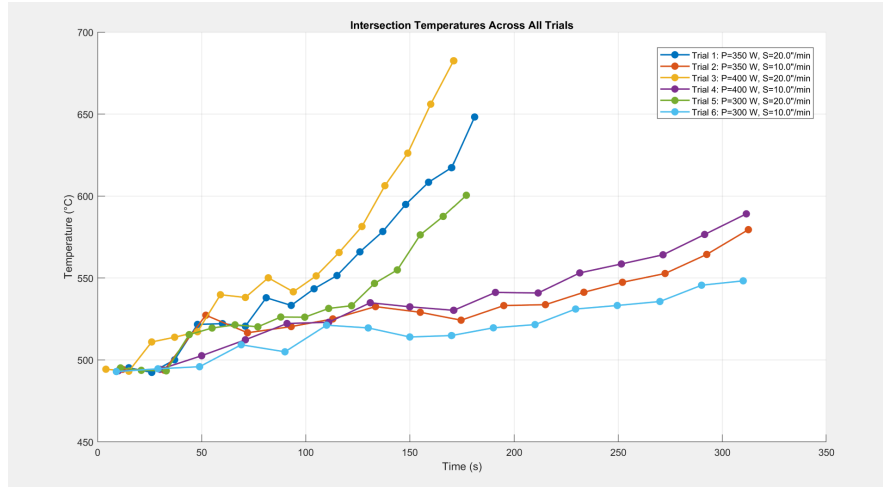


Figure 3.4: Effects of Different Process Parameters on the Temperature of the Bottom Center of Each Layer in the Experiment (Laser power, scanning speed, and dwell time)

3.2 Approaches to Finite Element Modelling for Different Printing Materials and Parameters

The FE model demonstrates robust transferability. Through the calibration of pivotal parameters in the finite element (FE) model to stainless steel 316, adjusting the process parameters to match the experimental data, the temperature change process from the midpoint to the end of each layer is almost identical, starting from the sixth layer as shown in Figure 3.5. The model's flexibility is primarily manifested in its parameterized design, allowing users to tailor settings according to specific requirements.

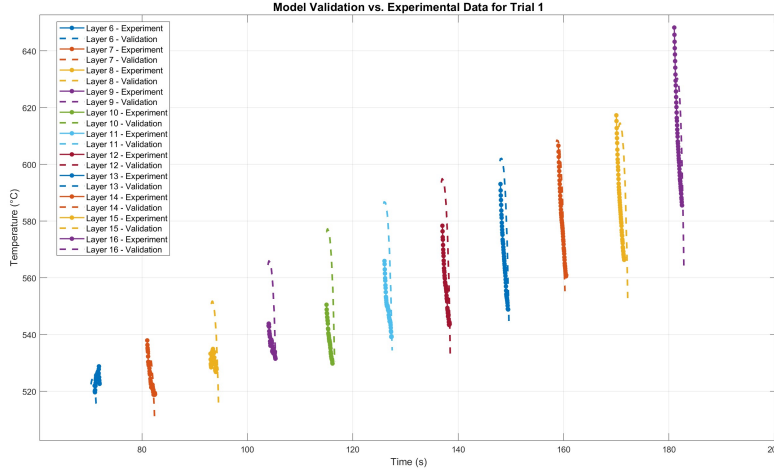


Figure 3.5: Validation of FE Model with Experiment Data

Key adjustable parameters include material thermophysical properties (thermal conductivity, heat capacity, density, and temperature dependence), process parameters (laser power, scanning speed, spot diameter), and heat source characteristics (absorption efficiency). For material systems, solidus/liq- uidus temperatures and latent heat are modified to capture phase transitions.

During model transfer, absorption efficiency (η_{power} , typically 0.3–0.7) requires careful consideration, along with boundary conditions such as convective coefficient (H_{conv}) and emissivity (ε). Default theoretical values often yield poor accuracy, so parameters must be calibrated against experiments (e.g., temperature fields, melt pool size, cooling rate) through iterative adjustment to improve predictive reliability.

Chapter 4

Establishment and Validation of the State-Space Model

Traditional control system design methods are based on analyzing the system's working mechanism and establishing a model of it. However, establishing an accurate mathematical model for complex industrial processes is often difficult, so system identification methods are necessary to establish the functional relationship between the system's inputs and outputs. Regardless of whether the controller is designed based on a mechanism model, it is necessary to first analyze and understand the system's characteristics before designing the controller. The impact of varying heat source parameters on the simulation process and outcomes is substantial, manifesting as effects on the temperature distribution and melt pool dimensions of metallic alloy materials, as well as on the residual stress and deformation of the formed material. To illustrate this phenomenon, consider the example of heat source power. When the power is high, the model generates higher temperatures and larger temperature gradients. Therefore, the primary objective of this chapter is to investigate the effects of different parameters on temperature and cooling rate.

4.1 Proposal of Discrete Temperature Prediction Model

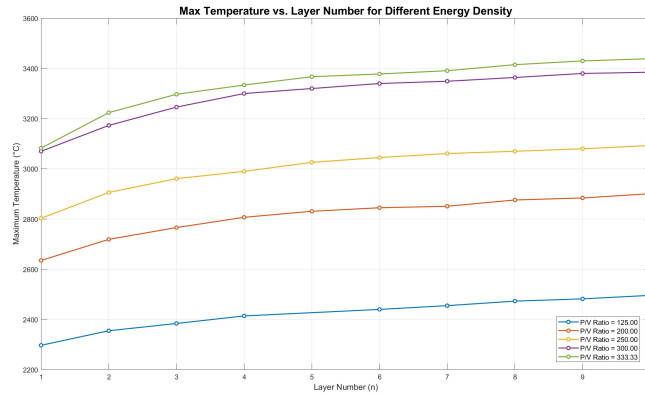
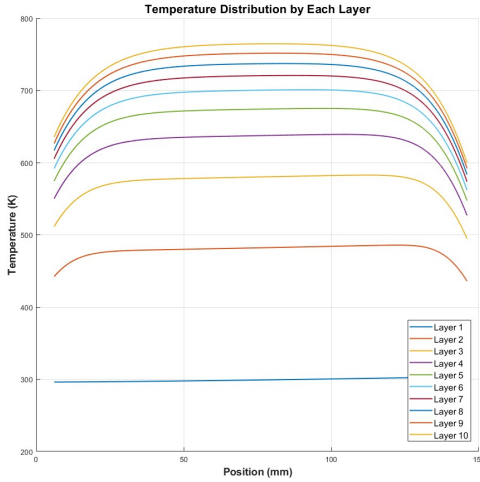


Figure 4.1: Effect of Energy Density on the Maximum Temperature of Each Layer by Simulation

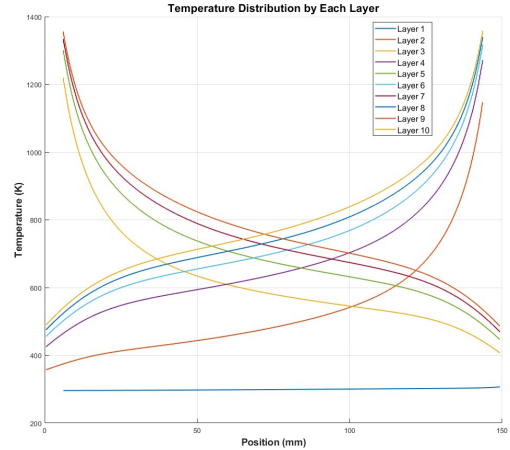
As shown in the Figure 4.1, as the laser scanning speed increases, the amount of heat received by the metal powder per unit time decreases. The maximum temperature in the molten pool also decreases. The heat input can be assessed using the laser energy density (E).

$$E_k = \frac{P_k}{V_k} \quad (4.1)$$

In Figure 4.2, the simulation results indicated that under identical input conditions, the temperature distribution between unidirectional and bidirectional printing exhibited a large difference. The discrepancy in temperature distribution was primarily attributable to the disparate cooling temperatures at each point during the printing process. Previous analysis suggests a correlation between the cooling temperature rate and an exponential function, based on the observed characteristics of the curve. Therefore, it can be inferred that the cooling function should be similar to the following format $e^{\lambda \Delta t}$, where λ is supposed to be related to the magnitude of the cooling rate, Δt refers to the total time for cooling.



(a) T_{init} Distribution by Layer for Unidirectional Printing



(b) T_{init} Distribution by Layer for Bidirectional Printing

Figure 4.2: Initial Temperature Distribution for Different Printing Types by Simulation

The pre-scan temperature for each layer is based on the previous input, temperature, and cooling time. Cooling occurs during the dwell time and the time it takes for the laser to move to the center of the corresponding area. In addition, it is evident that when the cooling time is infinite, the temperature will approach the ambient temperature. Therefore, the following formula results from combining the above processes:

$$T_{init,k+1} = e^{-\lambda \Delta t} (T_{init,k} - T_{ambient} + \alpha \frac{P_k}{v_k}) + T_{ambient} \quad (4.2)$$

4.1.1 Cooling Time for Unidirectional Printing

As illustrated in Figure 4.2, the temperature distribution can be divided into three distinct segments: the left, middle, and right layers. The temperature in each region is comparable. Therefore, the midpoint of each segment should be considered when calculating the total dwell time. In Figure 4.3

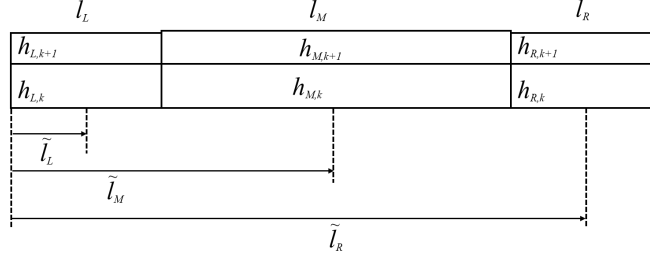


Figure 4.3: Simplified Layer Demonstration

It is assumed that all printing methods default to left-to-right orientation. Under this assumption, the sequence of heating is first the left region, then the middle region, and finally the right region for each layer. The midpoints of each region can be taken, and the cooling time, denoted by Δt , can be derived for each section.

For $k = 1, \dots, k - 1$:

$$\Delta t_{L,k} = \frac{L - \tilde{l}_L}{v_k} + \frac{\tilde{l}_L}{v_{k+1}} + \tau_k \quad (4.3)$$

$$\Delta t_{M,k} = \frac{L - \tilde{l}_M}{v_k} + \frac{\tilde{l}_M}{v_{k+1}} + \tau_k \quad (4.4)$$

$$\Delta t_{R,k} = \frac{L - \tilde{l}_R}{v_k} + \frac{\tilde{l}_R}{v_{k+1}} + \tau_k \quad (4.5)$$

4.1.2 Cooling Time for Bidirectional Printing

Assuming that bidirectional printing starts from left to right on the first layer, the heating sequence for odd layers is left end, middle, and right end, while for even layers, it is right end, middle, and left end.

Left-to-right: For $k = 1, 3, 5, \dots$

$$\Delta t_{L,k} = (L - \tilde{\ell}_L) \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.6)$$

$$\Delta t_{M,k} = (L - \tilde{\ell}_M) \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.7)$$

$$\Delta t_{R,k} = (L - \tilde{\ell}_R) \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.8)$$

Right-to-left: For $k = 2, 4, 6, \dots$

$$\Delta t_{L,k} = \tilde{\ell}_L \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.9)$$

$$\Delta t_{M,k} = \tilde{\ell}_M \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.10)$$

$$\Delta t_{R,k} = \tilde{\ell}_R \left(\frac{1}{|v_k|} + \frac{1}{|v_{k+1}|} \right) + \tau_k \quad (4.11)$$

4.2 Refinement and Validation of State Equations with Experimental Data

4.2.1 State Equation Adaptation for FE Model

The state equation model was validated by comparing its predictions against numerical results obtained from the finite element simulation. For both unidirectional and bidirectional printing strategies, temperature predictions at the left edge, center, and right edge of the print region are shown in Figures 5.1a, respectively. The complete set of fitted temperature profiles can be found in the Appendix A.

$$\begin{bmatrix} T_{\text{init},L,k+1} \\ T_{\text{init},M,k+1} \\ T_{\text{init},R,k+1} \end{bmatrix} = \begin{bmatrix} e^{-\lambda_L \Delta t_{L,k}} & 0 & 0 \\ 0 & e^{-\lambda_M \Delta t_{M,k}} & 0 \\ 0 & 0 & e^{-\lambda_R \Delta t_{R,k}} \end{bmatrix} \left(\begin{bmatrix} T_{\text{init},L,k} \\ T_{\text{init},M,k} \\ T_{\text{init},R,k} \end{bmatrix} + \begin{bmatrix} \alpha_L \\ \alpha_M \\ \alpha_R \end{bmatrix} \frac{P_k}{v_k} \right) \quad (4.12)$$

As summarized in the table below, the root mean square error (RMSE) and mean absolute error (MAE) were calculated for each location:

Location	RMSE (K)	MAE (K)
Center (T_k)	5.8574	4.6840
Left (T_l)	41.4563	30.6592
Right (T_r)	47.5920	35.1490

Table 4.1: Statistical result of state

The simulation results and state equation predictions in Figures 4.4 and 4.5 (all data from Table E.1) demonstrate a gradual increase in temperature with an increase in the number of layers. The figures demonstrate that the proposed model provides a reliable fit to the finite element simulation results, effectively capturing the underlying trends. Specifically, pre-scan temperature increases with both laser power and scanning speed, a behavior consistent with the experimental observations in Figure 3.4.

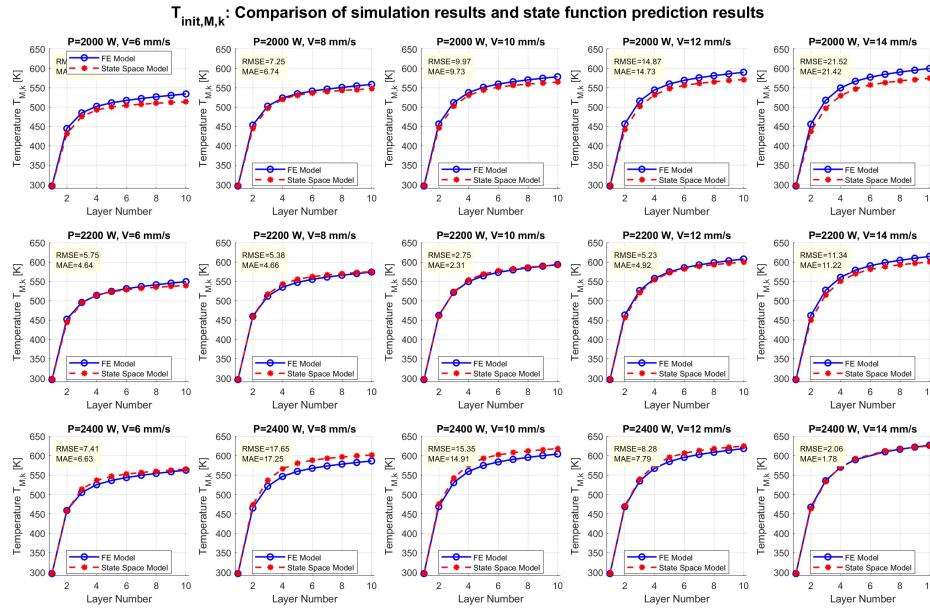


Figure 4.4: Temperature prediction results for $T_{init,M,k}$ in unidirectional printing using model 4.12 with constant λ and α .

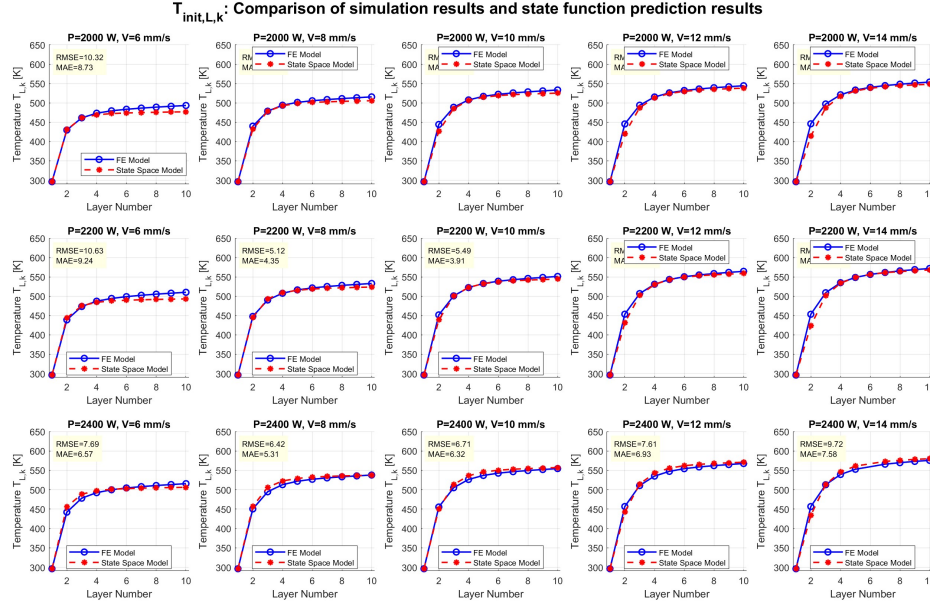


Figure 4.5: Temperature prediction results for $T_{init,L,k}$ in unidirectional printing using model 4.12 with constant λ and α .

4.2.2 State Equation Adaptation for Experiment Data

Given the benefits of 316 stainless steel powder, including its ease of processing and cost-effectiveness, the selection of 316 stainless steel powder as the additive manufacturing powder material for large-scale temperature measurement experiments is well-justified. The substrate material is also selected as 316 stainless steel. Table 4.2 presents the composition.

Table 4.2: Chemical composition of 316 stainless steel powder and substrate material (wt%)

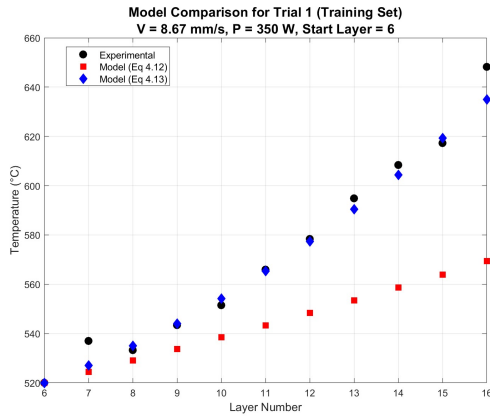
Element	C	Ni	Cr	Mo	Mn	Si	P	S	Fe
Mass fraction (%)	0.024	10.8	16.9	2.1	1.14	0.52	0.027	0.011	Bal

Deposition experiments were conducted using different laser powers, ranging from 300W to 400W. The mean temperature of the area before scanning during processing was collected by an IR camera. The process parameters are delineated in Table 4.3.

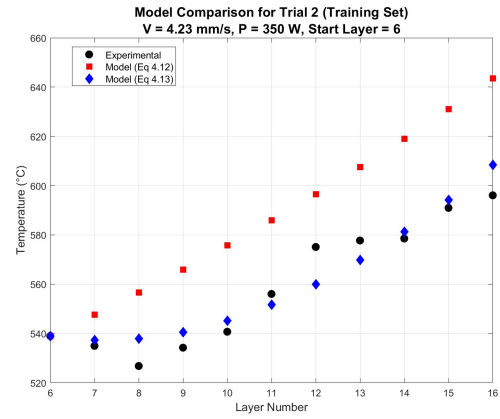
Table 4.3: Experimental Trials

Trial	1	2	3	4	5	6	7
Power (W)	350	350	400	400	300	300	300
Speed (mm/s)	8.67	4.23	8.67	4.23	8.67	4.23	8.67
Dwell (s)	2	2	2	2	2	2	120
Layer Height (mm)	0.381	0.381	0.381	0.381	0.381	0.381	0.381

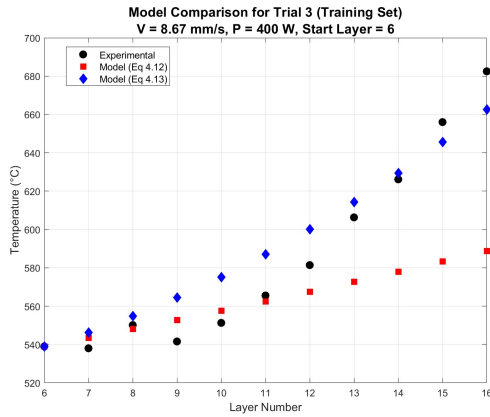
The six trials from the sample were divided into a training group and a test group. The first four trials were used for training, and the last trial was used for testing to validate and improve the model. The findings of the fitting process indicate that when both α and λ in Equation xx are constants, achieving precise alignment with the experimental data becomes challenging. Therefore, to improve accuracy, it is necessary to modify α and λ into variables that are strongly correlated with the corresponding terms. The analysis of the cooling rate indicates a correlation between the cooling speed and the initial temperature, as well as the laser movement speed before the printing process. Consequently, a modification of λ was executed, rendering it a function of $T_{init,k}$ and v_k . Concurrently, the parameter α may undergo variation by the accumulation of heat as the number of layers increases. Therefore, the parameter α is designated as a function associated with the layer number for fitting. A comparison of the initial model, results in Figure 4.6 and Table 4.4 below, with the updated model reveals the latter's superior precision and capacity to provide a more stable fit to the experimental data.



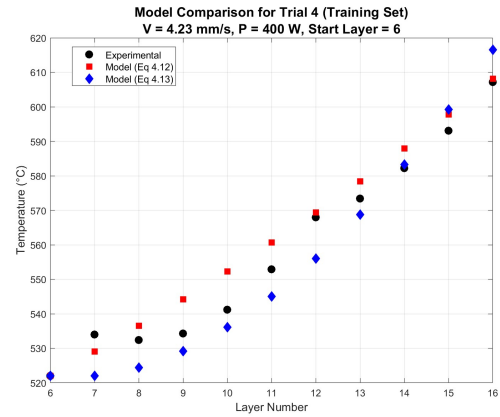
(a) Fitting results of Trial 1



(b) Fitting results of Trial 2

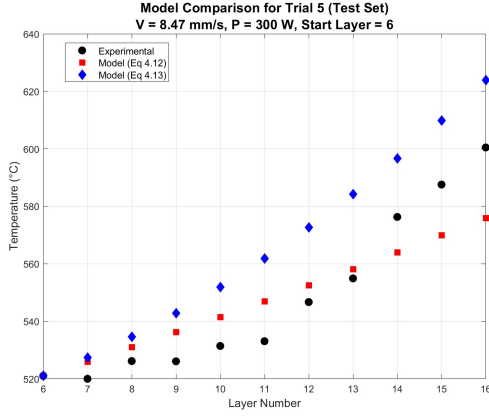


(c) Fitting results of Trial 3

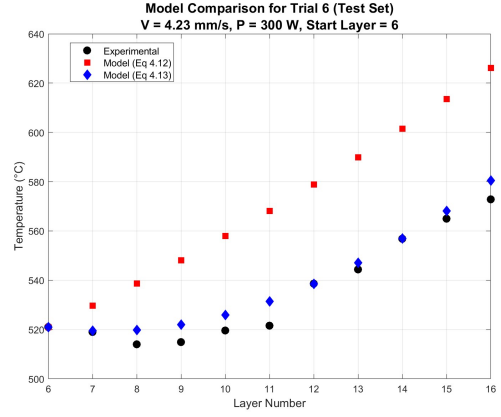


(d) Fitting results of Trial 4

Figure 4.6: Recursive Simulation Comparison between Model (Eq 4.12) and Model (Eq 4.13) Using Training Set Results from Experiment Trial 1–4.



(a) Fitting results of Trial 5



(b) Fitting results of Trial 6

Figure 4.7: Recursive Simulation Comparison between Model (Eq 4.12) and Model (Eq 4.13) Using Test Set Results from Experiment Trial 5–6.

	Training Set MAE (°C)	Test Set MAE (°C)
Model (Eq 4.12)	22.2633	22.4649
Model (Eq 4.13)	7.3384	11.2007

Table 4.4: Performance Metrics

where Model (Eq 4.12) represents the basic model, with $\alpha = -0.0654$, $\lambda = -0.001971$

Following (Eq 4.13) represents the improvement, with λ and α changing in terms of layer number (k), scan velocity (v) and pre-scan temperature ($T_{init,k}$)

$$T_{init,M,k+1} = e^{-\lambda_n(v_k, T_{init,M,k})\Delta t_k} \left(T_{init,M,k} - T_{ambient} + \alpha_k \frac{P_k}{v_k} \right) + T_{ambient} \quad (4.13)$$

$$\lambda_k = \beta_1 v_k + \beta_2 T_{init,M,k} + \beta_3 \quad (4.14)$$

$$\alpha_k = \gamma_1 k + \gamma_2 \quad (4.15)$$

where $\beta_1 = 0.000005$, $\beta_2 = -0.000473$, $\beta_3 = 0.0005$, $\gamma_1 = 0.0264$, $\gamma_2 = -0.0906$.

4.3 Modelling of Liquid-Solid Solidification Cooling Rates

The rate at which metal transitions from a liquid state to a solid state exerts a substantial influence on the process of crystallization, consequently affecting the microstructure of the alloy. Consequently, the cooling rate constitutes a pivotal focal point of this study. In the state-space equations utilized in this study, the output equation signifies the cooling rate during the solidification period. Given

the inherent difficulty of measuring the cooling temperature of each layer in experiments, the cooling rates in this study are all based on results from FE model simulations. The calculation process is included in the Appendix C.

4.3.1 Analysis of Factors Influencing Solidification Cooling Rates

The cooling rate depends on both material properties and process parameters, but considering all simultaneously is impractical. Following Kummail et al.[8], this study focuses on laser power, laser velocity, and $T_{init,k}$ as key variables. By plotting velocity and $T_{init,k}$ on the x-y axes and cooling rate on the z-axis, their independent relationships can be clearly visualized.

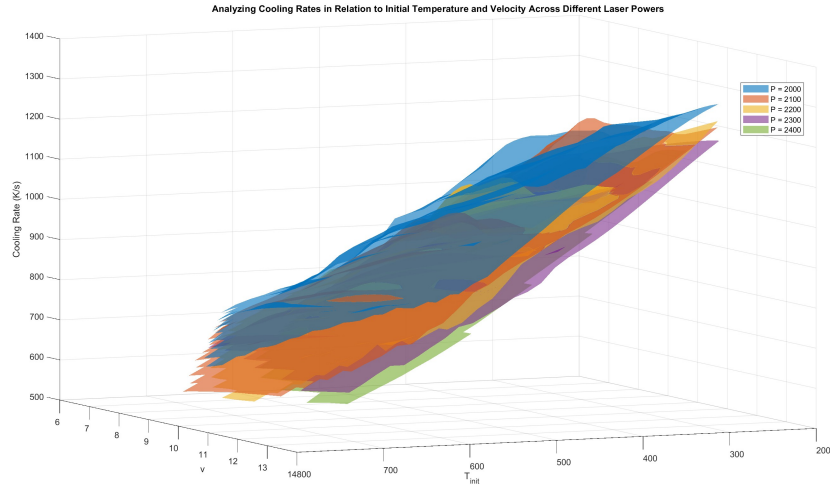


Figure 4.8: 3D Relationship between Cooling Rate and Scanning Speed, Initial Temperature and Power

The relationship between cooling rate and scanning speed is best understood by controlling each variable individually. Among process parameters, scanning speed exerts the most significant influence. As shown in Figure 4.2, the exponential function provides a more accurate description of the cooling rate–speed relationship than the quadratic model, and also reveals distinct patterns. Thus, the exponential function is adopted to model this dependence.

The predictive model for cooling rate (CR) is based on heat transfer principles and empirical observations. Since heat flow ($\dot{q}$) is directly linked to the temperature gradient, the cooling rate is expected to exhibit a non-linear dependence on the melt pool temperature (T_m), for which a polynomial model is appropriate. In contrast, laser power (P) acts mainly as a secondary factor, and its effect can be sufficiently captured by a linear relationship.

Based on this reasoning, a semi-empirical model was developed that is quadratic concerning tem-

perature and linear concerning power. To ensure numerical stability and prevent issues arising from disparate variable scales during the fitting process, all independent variables (V, T_m, P) were standardized.

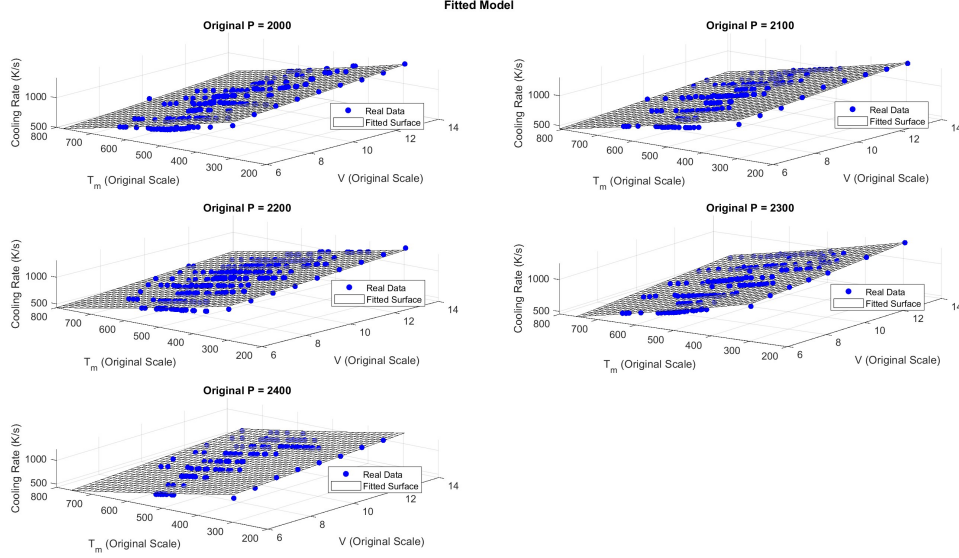


Figure 4.9: 3D fitting results between cooling rate and scanning speed, initial temperature and power

The final fitted model is given by the equation:

$$\begin{aligned} \text{CR} = & 422.6671 \cdot \exp(0.0726 \cdot V_s) - 51.8129 \cdot T_{m,s} \\ & + 7.9920 \cdot T_{m,s}^2 - 35.2017 \cdot P_s \end{aligned} \quad (4.16)$$

Where the standardized variables are defined as:

$$\begin{aligned} V_s &= \frac{V - 9.7124}{2.8734} \\ T_{m,s} &= \frac{T_m - 535.7838}{64.2418} \\ P_s &= \frac{P - 2197.9351}{129.3019} \end{aligned}$$

The proposed model showed satisfactory fitting, as seen in Figure 4.9 (all data from Table E.2), where simulation data align well with the predicted plane. It achieved an RMSE of 28.12, notably lower than the alternative model's 33.98. Owing to its higher accuracy and sound physical basis, the quadratic-temperature, linear-power model is adopted as the most suitable representation of the cooling rate.

Chapter 5

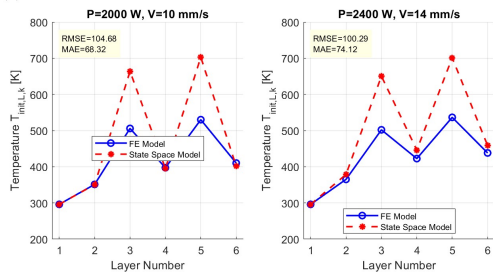
Conclusion

5.1 Summary

This study employed a thermal finite element analysis of the laser additive manufacturing process for Ti6Al4V alloy. The investigation focused on the evolution of the temperature field and the forming mechanism in components. The study analyzed the influence patterns of different process parameters, proposed corresponding optimization schemes for issues encountered during processing, and validated these through simulation. Furthermore, the study examined the solidification of the melt pool under various conditions, acquiring data regarding alterations in cooling temperature at the solidification interface. State-space equations for the Ti6Al4V processing process were established and cross-validated with experimental data from stainless steel 316 material. The steps for linearization and controllability are outlined in the Appendix B.

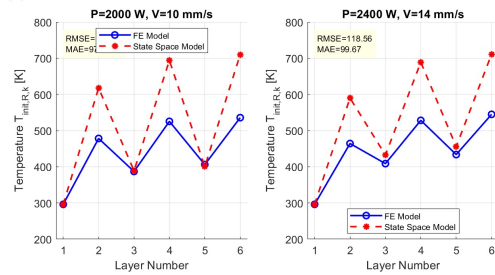
5.2 Limitation and Analysis

$T_{init,L,k}$: Comparison of Simulation Results and State Function Prediction Results



(a) T_{init} Distribution by Layer for Unidirectional Printing

$T_{init,R,k}$: Comparison of Simulation Results and State Function Prediction Results



(b) T_{init} Distribution by Layer for Bidirectional Printing

Figure 5.1: Temperature prediction results for $T_{init,L,k}$ and $T_{init,R,k}$ in bidirectional printing using model 4.12 with printing interval equals 10s.

Significant predictive deviations arise when using the state-space model for the extremities of the bidirectional scan path under conditions of long interlayer dwell times. As shown in Figure 5.1, when the print spacing is adjusted to 10s, the two ends of bidirectional printing will produce a significant

deviation from the simulation results of the FE model. This discrepancy is attributed to the inherent rapid convergence of the model's underlying exponential function, which may inaccurately represent the thermal rate during the complex cooling and reheating cycles experienced at these locations.

Evidence from experimental observations in Figure 4.4 suggests that the applicability of the exponential-based state-space model is strongest for the initial rapidly heated layers. Additionally, given the tendency for errors to accumulate with each successive layer, it is to be expected that the magnitude of the error will increase in proportion to the number of layers present. Furthermore, since phenomena such as remelting, which cause changes in geometric properties, are not taken into account, this state space equation is more suitable for situations with low power and fast scan speeds, thereby avoiding excessive changes in geometric properties.

5.3 Future Work

While this study has achieved certain results and conducted research in the field of LDED, it still has shortcomings. In light of this, the following sections will outline some prospects for future research content and directions.

- 1 The finite element method (FEM) thermal model does not account for the effects of metal powder, molten liquid flow, and solution evaporation on high-temperature fields and solidification states. Since the finite element method encounters considerable difficulties in the resolution of discontinuous media and liquid flow problems, future research endeavors will utilize methodologies such as the discrete element method and finite volume method to address issues related to metal powder and liquid flow.
- 2 The format of the state space equation is not without its flaws. To conduct a more thorough investigation, it is essential to determine the physical significance of λ and α , and to perform a detailed analysis and verification of their responses to various parameters.
- 3 Experimental calibration is an essential means of improving the accuracy and reliability of proxy models for training. Therefore, when conditions permit, the authors hope to obtain more experimental data to calibrate the computing platform established in this paper.
- 4 The ultimate objective of this study is to establish a closed-loop control system. In the future, research efforts and investment in this area will be augmented to construct a closed-loop research platform. A potential solution is posited in the Appendix. D.

Bibliography

- [1] *Simulations of Thermo-Mechanical Characteristics in Electron Beam Additive Manufacturing*, volume Volume 3: Design, Materials and Manufacturing, Parts A, B, and C of *ASME International Mechanical Engineering Congress and Exposition*, 11 2012.
- [2] Amit Bandyopadhyay and Kellen D. Traxel. Invited review article: Metal-additive manufacturing—modeling strategies for application-optimized designs. *Additive Manufacturing*, 22:758–774, 2018.
- [3] Bernd Baufeld, Omer Van der Biest, and Rosemary Gault. Additive manufacturing of ti-6al-4v components by shaped metal deposition: Microstructure and mechanical properties. *Materials Design*, 31:S106–S111, 2010. Advanced Component Manufacture from Light Materials.
- [4] Guijun Bi, Bert Schürmann, Andres Gasser, Konrad Wissenbach, and Reinhart Poprawe. Development and qualification of a novel laser-cladding head with integrated sensors. *International Journal of Machine Tools and Manufacture*, 47(3):555–561, 2007.
- [5] David Bourell, Jean Pierre Kruth, Ming Leu, Gideon Levy, David Rosen, Allison M. Beese, and Adam Clare. Materials for additive manufacturing. *CIRP Annals*, 66(2):659–681, 2017.
- [6] Chao Guo, Wenjun Ge, and Feng Lin. Effects of scanning parameters on material deposition during electron beam selective melting of ti-6al-4v powder. *Journal of Materials Processing Technology*, 217:148–157, 2015.
- [7] J.C. Heigel, P. Michaleris, and E.W. Reutzel. Thermo-mechanical model development and validation of directed energy deposition additive manufacturing of ti-6al-4v. *Additive Manufacturing*, 5:9–19, 2015.
- [8] John Kummailil, Carmine Sammarco, David Skinner, Christopher A. Brown, and Kevin Rong. Effect of select lensTM processing parameters on the deposition of ti-6al-4v. *Journal of Manufacturing Processes*, 7(1):42–50, 2005.
- [9] I.A. Roberts, C.J. Wang, R. Esterlein, M. Stanford, and D.J. Mynors. A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing. *International Journal of Machine Tools and Manufacture*, 49(12):916–923, 2009.
- [10] P. Rochus, J.-Y. Plessier, M. Van Elsen, J.-P. Kruth, R. Carrus, and T. Dormal. New applications of rapid prototyping and rapid manufacturing (rp/rm) technologies for space instru-

mentation. *Acta Astronautica*, 61(1):352–359, 2007. Bringing Space Closer to People, Selected Proceedings of the 57th IAF Congress, Valencia, Spain, 2-6 October, 2006.

- [11] Waheed Ul Haq Syed, Andrew J. Pinkerton, and Lin Li. A comparative study of wire feeding and powder feeding in direct diode laser deposition for rapid prototyping. *Applied Surface Science*, 247(1):268–276, 2005. Proceedings of the European Materials Research Society 2004 - Symposium N.
- [12] G. Welsch, R. Boyer, and E.W. Collings. *Materials Properties Handbook: Titanium Alloys*. Materials properties handbook. ASM International, 1993.

Appendix A

Supplement Figures

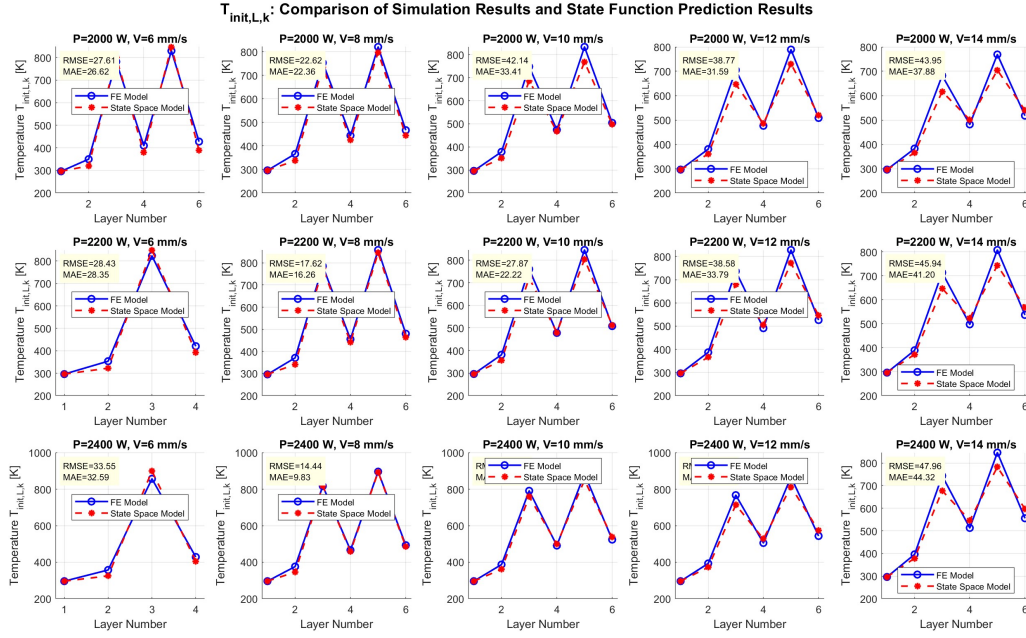


Figure A.1: Temperature prediction results for $T_{init,L,k}$ in bidirectional printing model 4.12 with constant λ and α .

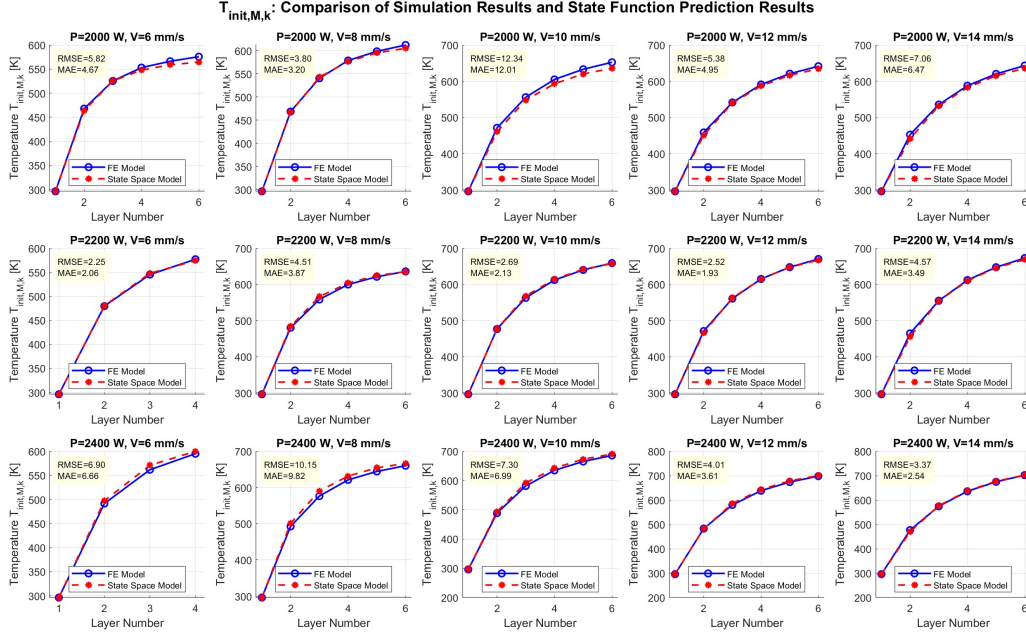


Figure A.2: Temperature prediction results for $T_{init,M,k}$ in bidirectional printing model 4.12 with constant λ and α .

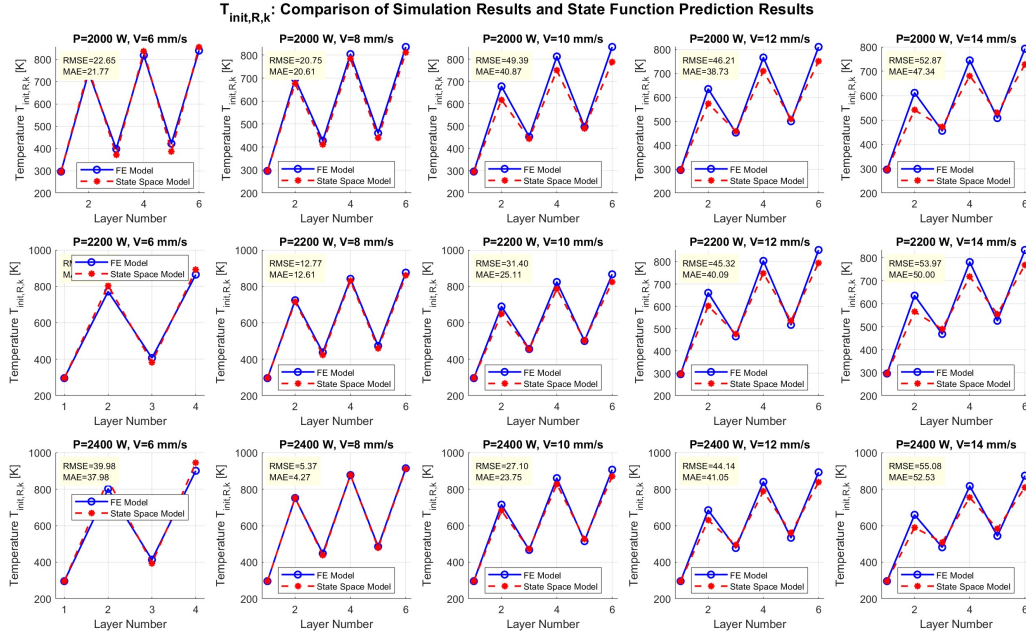


Figure A.3: Temperature prediction results for $T_{init,R,k}$ in bidirectional printing model 4.12 with constant λ and α .

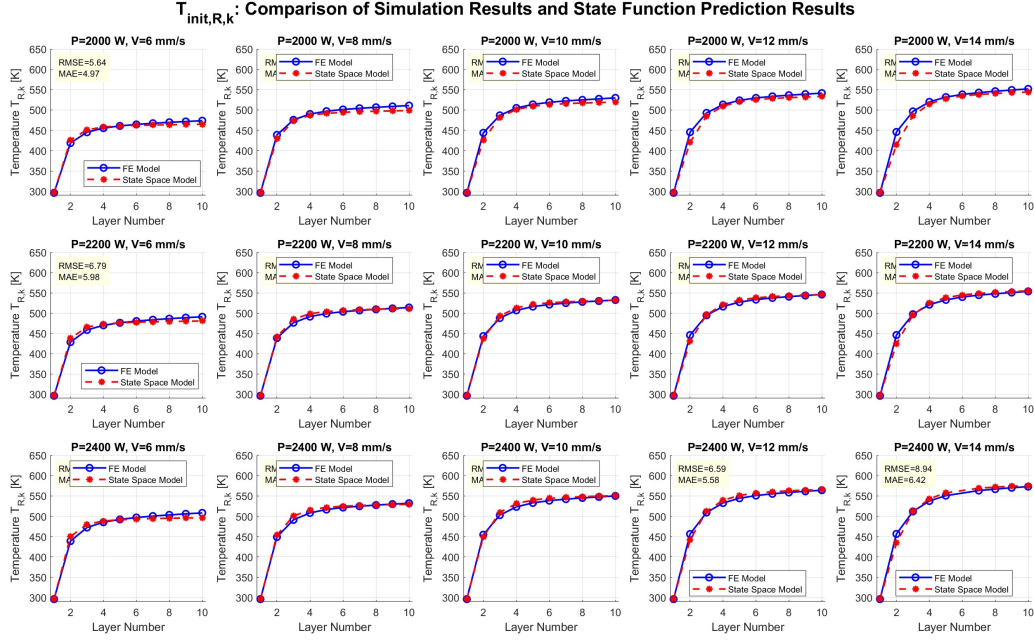
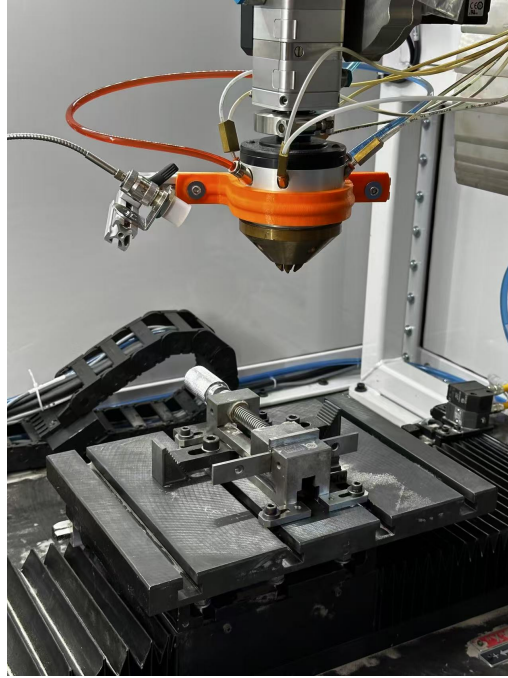
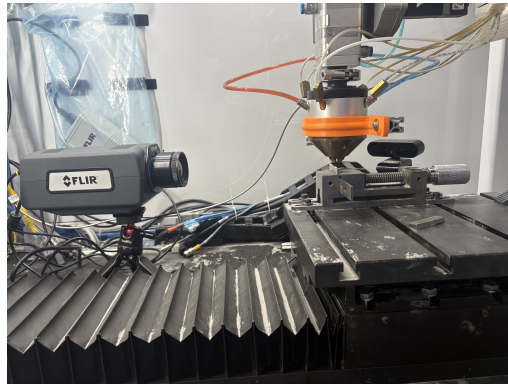


Figure A.4: Temperature prediction results for $T_{init,R,k}$ in unidirectional printing model 4.12 with constant λ and α .



(a)



(b)



(c)

Figure A.5: Experimental setup showing the main components: (a) Head and Substrate, (b) IR Camera Set up (c) Temperature data acquisition system for signal processing and measurement recording

Appendix B

Linearization Process

B.1 Linearization Procedure

We linearize the system around a nominal operating point $(x_0, \mathbf{u}_0, k_0)$, which corresponds to $(T_0, P_0, v_0, \tau_0, k_0)$.

First, we define the operating point values for the intermediate variables:

$$\begin{aligned}\lambda_0 &= \beta_1 v_0 + \beta_2 T_0 + \beta_3 \\ \alpha_0 &= m k_0 + n \\ \Delta t_0 &= L/v_0 + \tau_0 \\ S_0 &= T_0 - T_{\text{ambient}} + \alpha_0 \frac{P_0}{v_0} \quad (\text{The crucial helper term, now updated})\end{aligned}$$

Matrix A: State Matrix

$A = \left. \frac{\partial f}{\partial x_k} \right|_0 = \left. \frac{\partial f}{\partial T_k} \right|_0$. The final additive T_{ambient} term has a derivative of zero with respect to T_k .

$$\begin{aligned}\frac{\partial f}{\partial T_k} &= \frac{\partial}{\partial T_k} \left[e^{-\lambda_k \Delta t_k} \right] \left(T_k - T_{\text{ambient}} + \alpha_k \frac{P_k}{v_k} \right) + e^{-\lambda_k \Delta t_k} \frac{\partial}{\partial T_k} [T_k - T_{\text{ambient}} + \dots] \\ &= \left(e^{-\lambda_k \Delta t_k} (-\Delta t_k) \frac{\partial \lambda_k}{\partial T_k} \right) (T_k - T_{\text{ambient}} + \dots) + e^{-\lambda_k \Delta t_k} (1) \\ &= e^{-\lambda_k \Delta t_k} \left(1 - \beta_2 \Delta t_k \left(T_k - T_{\text{ambient}} + \alpha_k \frac{P_k}{v_k} \right) \right)\end{aligned}$$

Evaluating at the operating point using the helper term S_0 :

$$A = e^{-\lambda_0 \Delta t_0} [1 - \beta_2 \Delta t_0 S_0] \tag{B.1}$$

Matrix B: Input Matrix

$$B = \left. \frac{\partial f}{\partial \mathbf{u}_k} \right|_0 = \left[\begin{array}{ccc} \frac{\partial f}{\partial P_k} & \frac{\partial f}{\partial v_k} & \frac{\partial f}{\partial \tau_k} \end{array} \right]_0.$$

Term 1: $\partial f / \partial P_k$

$$\frac{\partial f}{\partial P_k} = e^{-\lambda_k \Delta t_k} \left(\frac{\alpha_k}{v_k} \right) \implies B_1 = e^{-\lambda_0 \Delta t_0} \frac{\alpha_0}{v_0}$$

Term 2: $\partial f / \partial v_k$ The derivation logic is identical to the previous step, but we use the new definition of the term in the main parenthesis (now represented by S_0).

$$\frac{\partial f}{\partial v_k} = e^{-\lambda_k \Delta t_k} \left[\left(\frac{\lambda_k L}{v_k^2} - \beta_1 \Delta t_k \right) \left(T_k - T_{\text{ambient}} + \alpha_k \frac{P_k}{v_k} \right) - \frac{\alpha_k P_k}{v_k^2} \right]$$

Evaluating at the operating point:

$$B_2 = e^{-\lambda_0 \Delta t_0} \left[\left(\frac{\lambda_0 L}{v_0^2} - \beta_1 \Delta t_0 \right) S_0 - \frac{\alpha_0 P_0}{v_0^2} \right]$$

Term 3: $\partial f / \partial \tau_k$

$$\begin{aligned} \frac{\partial f}{\partial \tau_k} &= \left(T_k - T_{\text{ambient}} + \alpha_k \frac{P_k}{v_k} \right) \cdot \left(e^{-\lambda_k \Delta t_k} \cdot (-\lambda_k) \cdot \frac{\partial \Delta t_k}{\partial \tau_k} \right) \\ &= -\lambda_k e^{-\lambda_k \Delta t_k} \left(T_k - T_{\text{ambient}} + \alpha_k \frac{P_k}{v_k} \right) \end{aligned}$$

Evaluating at the operating point:

$$B_3 = -\lambda_0 e^{-\lambda_0 \Delta t_0} S_0$$

The complete input matrix B is $\begin{bmatrix} B_1 & B_2 & B_3 \end{bmatrix}$.

Matrix C and D: Output and Feedforward Matrices

The output equation $g(x_k, \mathbf{u}_k)$ has not changed. Therefore, its partial derivatives with respect to the state and inputs are identical to the previous calculations.

$$C = \begin{bmatrix} 15.984T_0 - 51.8129 \end{bmatrix} \tag{B.2}$$

$$D = \begin{bmatrix} -35.2017 & 30.6849e^{0.0726v_0} & 0 \end{bmatrix} \tag{B.3}$$

B.2 Controllability Analysis

The state-space dimension remains $n = 1$.

Controllability

The controllability matrix is $\mathcal{C} = B$. The system is controllable if B is not a zero vector. While the expressions for B_2 and B_3 now depend on the new helper term S_0 , the fundamental argument for controllability remains unchanged and is in fact stronger. For the system to be uncontrollable, all three elements of B must be zero simultaneously. The conditions for each element being zero are algebraically distinct and depend on different combinations of the operating point variables. It is practically impossible to find a physical operating point $(T_0, P_0, v_0, \tau_0, k_0)$ that would satisfy these different conditions simultaneously.

Conclusion: The system is robustly **controllable** for all practical operating points.

Appendix C

Cooling Rate Calculation

The analysis begins by identifying the maximum temperature and its corresponding time ($t_{\max}$) for each cell. Upon detecting a new maximum, the timestamps for phase transitions are reset. The time at which the temperature drops below the liquidus temperature ($T_{\text{liquidus}} = 1928 \text{ K}$) is determined only if the maximum temperature exceeds this threshold. Linear interpolation is applied at the liquidus crossing point to enhance temporal accuracy. Similarly, the time when the cell cools to the solidus temperature ($T_{\text{solidus}} = 1878 \text{ K}$) is determined using the same interpolation method.

Cooling rates are computed based on the phase transition behaviour:

- If a full liquid-to-solid transition occurs:

$$\text{cooling_rate} = \frac{T_{\text{liquidus}} - T_{\text{solidus}}}{t_{\text{solid}} - t_{\text{liquid}}}$$

- Otherwise, if the cell does not experience a liquid phase:

$$\text{cooling_rate} = \frac{T_{\max} - T_{\text{solidus}}}{t_{\max} - t_{\text{liquid}}}$$

Appendix D

Closed-loop Control Scheme

After establishing the discrete state-space model, implementing control theory requires designing the entire LDED system as a closed-loop system. This study proposes developing a control system using the dSPACE real-time control platform, which integrates seamlessly with the MATLAB/Simulink environment. This platform enables real-time implementation and testing of advanced control strategies within the familiar Simulink modelling framework.

Considering the difficulty of implementation and the processing results, it is most appropriate to use laser power as the control parameter for the molten pool temperature control system. To implement closed-loop temperature control, real-time melt pool temperature data must be acquired and transmitted to the dSPACE real-time controller. This can be achieved using a high-temperature pyrometer. Communication between the pyrometer and the dSPACE controller can be established either via analog/digital (A/D) converters or serial communication interfaces such as RS232 or RS485.

Although A/D and D/A converters typically offer high precision, they can still introduce errors during signal conversion. Additionally, analog voltage signals are susceptible to electromagnetic noise during transmission. To mitigate such issues, RS232 serial communication is recommended due to its robustness against noise and higher transmission accuracy.

Start Bit										Stop Bit
0	LSB	D1	D2	D3	D4	D5	D6	MSB	Odd/Even	1

Figure D.1: RS232 Serial Communication Protocol

When using RS232 communication, both the pyrometer and dSPACE controller must adhere to a compatible serial communication protocol. The general structure of such a protocol is illustrated in Figure D.1, consisting of a data frame that includes one start bit, 1–8 data bits, one parity bit, and 1–2 stop bits. The most significant bit (MSB) and least significant bit (LSB) denote the data order. In this setup, both devices were configured to use a baud rate of 115200 bits/s, with 8 data bits, 1 stop bit, and odd parity. As illustrated in Figure D.2, upon receiving the request command, the colorimetric high-temperature meter transmits the melt pool temperature to dSPACE. After the reception of the melt pool temperature information in ASCII characters, dSPACE undertakes the conversion of the ASCII characters into double-precision floating-point numbers.

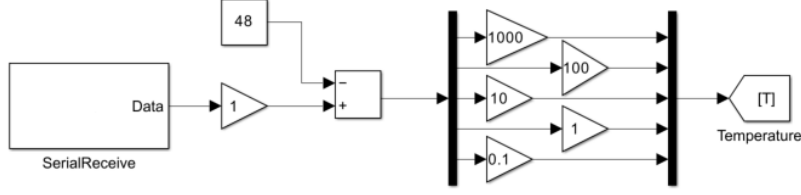


Figure D.2: Information Received by dSPACE Serial Port from Colorimetric Thermometer

The dSPACE controller is also responsible for sending real-time laser power control signals to the laser source. This communication is achieved through analog output signals. In the current experiment, the IPG YLS-4000 laser system, which includes an analog interface for power modulation, was used.

After building the real-time melt pool temperature control system, a stochastic excitation signal was applied to the system under open-loop conditions. Input and output data were collected to perform system identification. The resulting multiple-input, multiple-output (MIMO) data was used to derive a predictive model based on the identified state-space representation. This model serves as the foundation for implementing model predictive control (MPC) strategies in future closed-loop experiments.

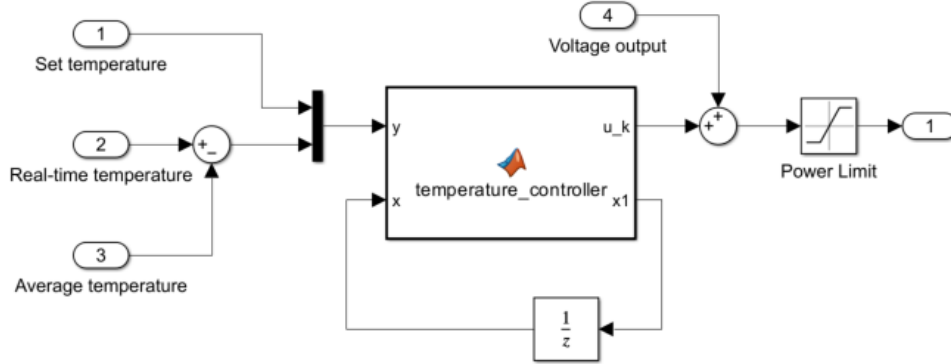


Figure D.3: Simulink Control Strategy for Prototyping Experiments

Appendix E

FE Model Simulation Data

Table E.1: Temperature Data of Simulation Results.

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	6	10	323.2422252	323.2666854	323.2678568	1	598.4674754	uni ¹
2200	6	10	438.9595892	452.3682713	428.6668221	2	476.1798874	uni
2200	6	10	473.5380389	495.5062023	458.4579388	3	432.4652201	uni
2200	6	10	487.2095106	513.9230878	470.0496052	4	414.0794881	uni
2200	6	10	494.3090495	524.1164579	476.2312438	5	403.1873227	uni
2200	6	10	498.9561019	531.1328761	480.4487243	6	395.7722478	uni
2200	6	10	502.5344244	536.5940439	483.7188926	7	389.7780912	uni
2200	6	10	505.4422446	541.260164	486.425733	8	384.742181	uni
2200	6	10	507.906682	545.4325817	488.8783258	9	380.166153	uni
2200	6	1	510.2380437	549.3390987	490.9921195	10	375.8416624	uni
2200	8	10	323.1543884	323.1554348	323.1554246	1	681.4932326	uni
2200	8	10	447.7877335	459.6104393	438.6328874	2	523.2041485	uni
2200	8	10	490.2838849	511.6465125	476.3944642	3	465.2290448	uni
2200	8	10	507.7434223	534.9358906	491.5273666	4	438.8411595	uni
2200	8	10	516.4016265	547.3356547	498.9712538	5	424.3962951	uni
2200	8	10	521.5607045	555.2566662	503.6077489	6	415.0902467	uni
2200	8	10	525.2081792	561.0708248	506.8052343	7	408.057784	uni
2200	8	10	528.1311427	565.8652574	509.3896214	8	402.4269283	uni
2200	8	10	530.6263208	570.1297615	511.6731189	9	397.5164816	uni
2200	8	1	533.0647833	574.1053299	513.9205153	10	393.2238046	uni
2200	10	10	323.1502611	323.1503193	323.1503184	1	715.8826028	uni
2200	10	10	451.7669829	462.1267858	443.4149971	2	535.3648751	uni
2200	10	10	500.9373891	521.6758272	487.9339469	3	469.2492968	uni
2200	10	10	522.3646689	549.5573975	506.9046993	4	439.9729551	uni
2200	10	10	532.9349719	564.2784714	516.2073083	5	424.166308	uni
2200	10	10	538.8734452	573.2767	521.2526593	6	414.3112424	uni
2200	10	10	542.8039194	579.6499232	524.8981411	7	407.7786157	uni

Continued on next page

¹uni represents unidirectional printing

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	10	10	546.0520888	584.7451806	527.8085549	8	402.6486815	uni
2200	10	10	548.6621864	589.1769718	530.0202826	9	398.1572161	uni
2200	10	1	551.2479167	593.3295722	532.4351731	10	393.9899894	uni
2200	12	10	323.1500185	323.1500224	323.1500227	1	726.8290754	uni
2200	12	10	453.6212727	463.0781738	445.9467894	2	549.6321904	uni
2200	12	10	506.8832323	526.3681524	494.6782615	3	479.3609389	uni
2200	12	10	531.0995489	557.6502189	516.3759823	4	446.4038707	uni
2200	12	10	543.3675488	574.7685614	527.2357637	5	429.0445073	uni
2200	12	10	550.4231595	585.2550709	533.4545506	6	418.5275331	uni
2200	12	10	555.1028379	592.5693987	537.5816641	7	411.2991448	uni
2200	12	10	558.6721432	598.3172423	540.7563324	8	405.8608946	uni
2200	12	10	561.7139264	603.2409041	543.4954102	9	401.3228576	uni
2200	12	1	564.5059782	607.7281633	546.0219362	10	397.2307326	uni
2200	14	10	323.1500015	323.1500018	323.1500018	1	740.4781847	uni
2200	14	10	453.3837352	461.8240222	446.0268562	2	572.7989442	uni
2200	14	10	509.0660783	527.1372048	497.3491383	3	504.3627404	uni
2200	14	10	535.0805326	560.3385473	521.0462772	4	471.055032	uni
2200	14	10	548.6287828	578.8520899	532.7686095	5	452.8708864	uni
2200	14	10	556.4603383	590.3213446	539.8290192	6	441.9512202	uni
2200	14	10	561.5459186	598.3106958	544.5741999	7	434.4878047	uni
2200	14	10	565.6042937	604.4886694	547.7514015	8	428.9549844	uni
2200	14	10	568.9358086	609.7485048	550.8600582	9	424.1377845	uni
2200	14	1	571.8162558	614.5069102	553.7027026	10	419.7087356	uni
2000	6	10	323.2269194	323.2543695	323.2559231	1	650.0158559	uni
2000	6	10	429.9245505	444.8133627	418.6999114	2	529.0299207	uni
2000	6	10	461.3973905	485.1433886	445.2504359	3	487.5624964	uni
2000	6	10	473.4050248	501.9380562	455.4372151	4	469.3753856	uni
2000	6	10	479.5949008	511.066207	460.8179011	5	459.5481646	uni
2000	6	10	483.5831371	517.2762726	464.4385244	6	452.2231136	uni
2000	6	10	486.5835091	522.2483505	467.3123979	7	446.2499498	uni
2000	6	10	489.104924	526.5174406	469.6384387	8	441.0930388	uni
2000	6	10	491.3114023	530.3643385	471.6537097	9	436.650256	uni
2000	6	1	493.3595961	533.950188	473.5819365	10	432.5082706	uni
2000	8	10	323.1538843	323.1551746	323.1551885	1	733.1850027	uni
2000	8	10	439.8951079	453.5222113	438.637102	2	577.1299337	uni
2000	8	10	478.6659166	502.3101781	475.6489402	3	523.5872584	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2000	8	10	494.0541417	523.4920233	489.9947311	4	500.4004849	uni
2000	8	10	501.4517632	534.5052483	496.9907607	5	487.4353394	uni
2000	8	10	505.6275256	541.4252871	501.2178897	6	478.7370574	uni
2000	8	10	508.7095642	546.5436592	504.1821125	7	472.1617429	uni
2000	8	10	511.2132702	550.865029	506.5723965	8	465.9753093	uni
2000	8	10	513.4467042	554.8938098	508.7446974	9	460.7711073	uni
2000	8	1	515.6108634	558.6543174	510.8768231	10	456.1115803	uni
2000	10	10	323.1502266	323.1502956	323.1502956	1	772.9663898	uni
2000	10	10	444.3247087	456.4720481	443.7417535	2	600.9540729	uni
2000	10	10	488.7274505	511.6294484	486.7400666	3	532.7369589	uni
2000	10	10	507.7288984	537.438955	504.8618259	4	501.9234012	uni
2000	10	10	516.9633884	551.12039	513.7199902	5	485.6590938	uni
2000	10	10	522.3689774	559.5262616	518.8496813	6	475.5890568	uni
2000	10	10	525.8880987	565.513106	522.3682465	7	468.0231977	uni
2000	10	10	528.6307691	570.3298444	524.8708079	8	462.3881722	uni
2000	10	10	531.0997891	574.5856222	527.3735505	9	457.9318039	uni
2000	10	1	533.4902467	578.4940472	529.7523266	10	453.6093117	uni
2000	12	10	323.1500158	323.1500202	323.1500202	1	796.3886408	uni
2000	12	10	445.5905943	456.5668159	445.4454627	2	620.7725487	uni
2000	12	10	494.0589171	515.6656505	492.8377055	3	551.9756667	uni
2000	12	10	515.3793834	544.2829195	513.402669	4	519.3304508	uni
2000	12	10	526.0439411	559.7292506	523.6254439	5	501.4955426	uni
2000	12	10	532.184594	569.2493264	529.6078231	6	490.5691812	uni
2000	12	10	536.1147001	575.9228065	533.4666957	7	483.000634	uni
2000	12	10	539.3302652	581.2011767	536.428167	8	477.2571189	uni
2000	12	10	541.8975584	585.7347712	538.9819093	9	472.1714028	uni
2000	12	1	544.4650241	589.9245687	541.4417149	10	467.8231013	uni
2000	14	10	323.1500013	323.1500017	323.1500017	1	809.0272625	uni
2000	14	10	445.969848	455.8706729	445.9301198	2	633.604771	uni
2000	14	10	497.213488	517.7618553	496.4764381	3	559.4111863	uni
2000	14	10	521.1111652	549.4964831	519.8895235	4	527.4682225	uni
2000	14	10	533.2989121	566.7540712	531.7224933	5	510.0764636	uni
2000	14	10	540.1805945	577.3209137	538.3689944	6	499.4190429	uni
2000	14	10	544.8359328	584.6921202	542.6546771	7	491.9532117	uni
2000	14	10	548.4777138	590.4442682	546.1143628	8	486.2133748	uni
2000	14	10	551.3491284	595.3491825	549.0967442	9	481.4149925	uni

Continued on next page

Table E.1: – *Continued from previous page*

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2000	14	1	553.9514564	599.7930284	551.8303594	10	477.0863855	uni
2400	6	10	323.2427929	323.2764654	323.2774634	1	558.6222938	uni
2400	6	10	442.1830747	458.8634137	438.9877517	2	424.251343	uni
2400	6	10	478.2073693	505.3618147	472.2411201	3	381.1476394	uni
2400	6	10	492.4852537	525.2653122	485.3116139	4	361.6999819	uni
2400	6	10	499.9171344	536.1620636	492.2422692	5	350.2825784	uni
2400	6	10	504.5663989	543.5815907	496.8662208	6	341.7563142	uni
2400	6	10	508.0298329	549.4496219	500.4374822	7	335.4686038	uni
2400	6	10	510.8934268	554.3217941	503.3028707	8	330.1574096	uni
2400	6	10	513.3671389	558.6666496	505.9304549	9	325.4386929	uni
2400	6	1	515.6401103	562.6913887	508.2382617	10	321.0877845	uni
2400	8	10	323.1544762	323.1559151	323.1559122	1	632.1214808	uni
2400	8	10	450.4798308	465.334824	448.9593822	2	465.1326525	uni
2400	8	10	494.7230435	521.2588621	491.0939217	3	404.8744208	uni
2400	8	10	513.0901306	546.4763441	508.2580463	4	379.5910859	uni
2400	8	10	521.9193674	559.528597	516.5878221	5	366.04785	uni
2400	8	10	526.9840494	567.6062382	521.4781523	6	357.3362617	uni
2400	8	10	530.5570623	573.472322	524.7421303	7	351.0562568	uni
2400	8	10	533.3464024	578.2598055	527.4678688	8	345.9789759	uni
2400	8	10	535.7016999	582.498636	529.884866	9	341.6013821	uni
2400	8	1	537.905279	586.4324303	532.0276738	10	337.6546774	uni
2400	10	10	323.1502702	323.1503563	323.1503542	1	654.2918355	uni
2400	10	10	455.3925723	468.7339195	454.5887072	2	481.3637244	uni
2400	10	10	505.1683916	530.5481559	502.8162018	3	416.9946903	uni
2400	10	10	526.5486956	559.449402	523.1287651	4	388.6844602	uni
2400	10	10	536.8936172	574.7557665	532.9019186	5	373.9046076	uni
2400	10	10	542.7685566	583.9346937	538.4844626	6	364.8178594	uni
2400	10	10	546.5773675	590.4562963	542.1691509	7	358.3956316	uni
2400	10	10	549.5689766	595.628188	545.1138537	8	353.3645229	uni
2400	10	10	552.1161326	600.1596737	547.622364	9	349.1242525	uni
2400	10	1	554.5640894	604.3147579	550.0573677	10	345.4782419	uni
2400	12	10	323.1500189	323.1500246	323.1500252	1	671.4265696	uni
2400	12	10	456.7163764	468.6252677	456.2546638	2	496.4627046	uni
2400	12	10	510.7991434	534.8137307	509.1675574	3	428.5325352	uni
2400	12	10	535.2066878	567.4570353	532.6207791	4	397.7486108	uni
2400	12	10	547.394894	585.0121341	544.2887464	5	381.5831305	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2400	12	10	554.307265	595.6756497	550.8663761	6	371.8330283	uni
2400	12	10	558.7933221	603.0589572	555.2705207	7	365.0720456	uni
2400	12	10	562.1102234	608.8279678	558.5696094	8	359.9370089	uni
2400	12	10	564.9697734	613.7659671	561.4349573	9	355.6696846	uni
2400	12	1	567.6072873	618.2724083	564.1116613	10	351.7434908	uni
2400	14	10	323.1500016	323.150002	323.150002	1	682.9832806	uni
2400	14	10	456.604314	467.4331288	456.5071257	2	520.3580312	uni
2400	14	10	512.8703623	535.4450866	511.7724615	3	451.1429927	uni
2400	14	10	539.3641565	570.3488928	537.547315	4	418.312158	uni
2400	14	10		589.7416528	550.6892347	5	400.1559413	uni
2400	14	10	560.6816252	601.8199635	558.1366819	6	389.381962	uni
2400	14	10	565.9248797	610.1541293	563.2843236	7	382.0836255	uni
2400	14	10	569.7989415	616.5798297	566.7893363	8	376.6098169	uni
2400	14	10	573.1073169	621.990323	570.1394895	9	372.1797289	uni
2400	14	1	575.8482986	626.8005862	573.0200194	10	368.1568663	uni
2100	6	10	323.2327808	323.2627128	323.2639505	1	619.5179379	uni
2100	6	10	433.3480676	448.81323	430.6113263	2	503.2239134	uni
2100	6	10	465.406392	489.9120606	460.2232722	3	459.566087	uni
2100	6	10	477.8022172	507.3032102	471.6280311	4	440.9005983	uni
2100	6	10	484.2837128	516.8464649	477.7255909	5	430.4301221	uni
2100	6	10	488.3796643	523.4198112	481.9531085	6	423.0025628	uni
2100	6	10	491.4747366	528.5891323	485.0835384	7	417.1112655	uni
2100	6	10	494.1545696	532.9885751	487.7500926	8	411.9359061	uni
2100	6	10	496.4446098	537.001382	490.083967	9	407.3626833	uni
2100	6	1	498.6112845	540.7305251	492.238852	10	403.3437588	uni
2100	6	10	323.2327808	323.2627128	323.2639505	1	619.5179379	bi ²
2100	6	10	365.6337825	459.1559649	595.6059995	2	536.6807376	bi
2100	6	10	612.7130403	499.092716	404.8593904	3	394.4157408	bi
2100	6	10	405.3494196	516.4187877	625.5864646	4	473.3169775	bi
2100	6	10	625.1479592	524.9927042	423.1472544	5	370.5647836	bi
2100	6	10	418.2492746	531.2613747	627.1819529	6	451.4250945	bi
2100	6	10	628.2777703	536.1081007	433.8838375	7	362.4718839	bi
2100	6	10	426.6381265	540.6218761	631.4249796	8	437.1489475	bi
2100	6	10	633.9089132	544.70261	441.8407527	9	355.6179263	bi
2100	6	1	433.0559191	548.7054804	637.9406046	10	426.1825663	bi

Continued on next page

²bi represents bidirectional printing

Table E.1: – *Continued from previous page*

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2100	8	10	323.1539667	323.1552616	323.1552622	1	710.4091321	bi
2100	8	10	379.79406	462.5457343	561.6813497	2	584.4737526	bi
2100	8	10	590.7894712	511.8439558	429.1225609	3	438.6254362	bi
2100	8	10	430.4133346	534.6156705	611.8661775	4	497.5781203	bi
2100	8	10	615.2055103	545.7319392	451.5992659	5	402.1384823	bi
2100	8	10	444.7822678	553.3915179	620.8046474	6	471.2971835	bi
2100	8	10	623.0897528	558.5887664	462.2692178	7	389.8732702	bi
2100	8	10	452.5634116	563.5128827	627.8609764	8	456.4849446	bi
2100	8	10	630.5468393	567.4901212	469.1140359	9	381.0697686	bi
2100	8	1	458.1228803	571.7782517	635.3117941	10	445.8332321	bi
2100	10	10	323.1502361	323.1503083	323.1503089	1	744.3305206	bi
2100	10	10	390.057679	463.4663754	540.8508758	2	600.6281588	bi
2100	10	10	578.1925009	519.8036041	446.5438938	3	454.7297267	bi
2100	10	10	449.1423598	547.4276092	605.8171755	4	493.4327957	bi
2100	10	10	612.2418824	561.4397881	473.4486398	5	409.6835865	bi
2100	10	10	465.3943165	570.5717816	620.3968625	6	463.9648197	bi
2100	10	10	623.658351	576.6168211	484.2912837	7	394.6547381	bi
2100	10	10	473.092996	582.0384963	629.2698489	8	449.4984645	bi
2100	10	10	632.1513587	586.3670401	490.8855666	9	384.7437883	bi
2100	10	1	477.8672225	590.7646888	637.2112715	10	439.6077798	bi
2100	12	10	323.1500165	323.1500212	323.1500216	1	758.9347377	bi
2100	12	10	397.3745597	463.0632188	526.1792716	2	615.3049906	bi
2100	12	10	568.7246741	523.0464114	457.8067076	3	474.5201138	bi
2100	12	10	462.2482896	554.3259093	600.2165091	4	498.1161042	bi
2100	12	10	609.4222445	570.82144	488.8458484	5	421.9558177	bi
2100	12	10	480.3259705	581.443592	619.408585	6	466.3484044	bi
2100	12	10	623.498224	588.5391596	500.562208	7	404.0075274	bi
2100	12	10	488.1926016	594.522953	629.7969556	8	451.3540724	bi
2100	12	10	632.6426105	599.2899174	506.8930236	9	393.136558	bi
2100	12	1	492.9594635	604.0000364	637.8173636	10	441.386007	bi
2100	14	10	323.1500014	323.1500018	323.1500018	1	773.8997271	bi
2100	14	10	402.2065483	461.3459577	514.1942214	2	621.0116897	bi
2100	14	10	561.4451018	524.7880294	465.667001	3	504.449702	bi
2100	14	10	471.0517023	557.4730881	595.1458275	4	518.1279618	bi
2100	14	10	605.407126	575.055643	498.7649089	5	451.7155351	bi
2100	14	10	490.2296627	586.4077495	616.3626094	6	487.2245656	bi

Continued on next page

Table E.1: – *Continued from previous page*

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2100	14	10	620.8348402	593.9875905	510.8493559	7	432.7100061	bi
2100	14	10	497.9991268	600.3296555	627.2274969	8	472.9431401	bi
2100	14	10	630.1182667	605.3065835	517.2728639	9	421.4214372	bi
2100	14	1	502.7312453	610.0879164	635.3602566	10	463.4696434	bi
2300	6	10	323.239013	323.2709757	323.2720408	1	577.9233099	bi
2300	6	10	367.8391221	466.3585335	609.6509642	2	486.5435877	bi
2300	6	10	627.9716254	509.5988147	410.1549718	3	339.9277903	bi
2300	6	10	410.7740383	528.7110996	642.4577959	4	417.8462795	bi
2300	6	10	642.0672159	538.1213554	429.6747766	5	314.5589693	bi
2300	6	10	424.3835498	544.7869297	644.2471386	6	395.8205593	bi
2300	6	10	645.2481169	549.995572	440.9642774	7	305.8710466	bi
2300	6	10	433.2942583	554.7522363	648.526753	8	381.3677139	bi
2300	6	10	651.1657957	559.0989738	449.4418218	9	299.0497234	bi
2300	6	1	440.0337958	563.2810425	655.3979288	10	369.9768542	bi
2300	8	10	323.1542835	323.1556485	323.155645	1	658.0331834	bi
2300	8	10	382.3821023	468.8950087	572.220563	2	528.8221894	bi
2300	8	10	602.5020524	521.6470111	435.0036442	3	377.7249098	bi
2300	8	10	436.3105895	546.5330487	626.2908413	4	435.266099	bi
2300	8	10	629.8774944	558.7364417	459.0035186	5	340.6830968	bi
2300	8	10	451.8866771	567.0691941	636.0148561	6	407.2342529	bi
2300	8	10	638.461144	572.7138861	470.3004615	7	328.740991	bi
2300	8	10	460.2117612	577.9821209	643.5464817	8	392.1061047	bi
2300	8	10	646.3542705	582.234472	477.7200606	9	320.403759	bi
2300	8	1	465.9846752	586.7033214	651.3882522	10	381.3462517	bi
2300	10	10	323.1502517	323.1503302	323.1503282	1	688.7312862	bi
2300	10	10	392.8555613	469.3303631	549.6835963	2	536.4828566	bi
2300	10	10	590.2036246	529.5585152	452.4100419	3	398.7855094	bi
2300	10	10	455.566077	558.8213971	619.4745594	4	435.4372266	bi
2300	10	10	626.2681663	573.4978928	480.9763344	5	355.4230653	bi
2300	10	10	472.7068485	583.1132576	634.7111513	6	406.7286051	bi
2300	10	10	638.0845736	589.5166499	492.7757407	7	341.2173313	bi
2300	10	10	480.6983065	595.1053385	643.9408998	8	393.5702007	bi
2300	10	10	646.7670004	599.5266872	499.4174551	9	331.9193204	bi
2300	10	1	485.7264292	604.1516681	652.0332125	10	383.4098722	bi
2300	12	10	323.1500183	323.1500237	323.1500244	1	695.986436	bi
2300	12	10	400.6421051	469.3780407	535.1012089	2	548.5006863	bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2300	12	10	580.3280536	533.3743951	464.7449329	3	418.9992138	bi
2300	12	10	469.0585258	565.9357355	613.591325	4	441.0488848	bi
2300	12	10	622.7609151	583.00235	496.92973	5	371.0557825	bi
2300	12	10	487.8928537	593.9514083	633.0668915	6	411.5478038	bi
2300	12	10	637.0928932	601.2119123	509.0012772	7	354.8445108	bi
2300	12	10	496.0157005	607.3317878	643.5931147	8	397.9309621	bi
2300	12	10	646.5152553	612.1407674	515.4362966	9	344.984275	bi
2300	12	1	501.0171345	617.0190575	651.8171343	10	388.8542844	bi
2300	14	10	323.1500015	323.1500019	323.1500019	1	708.2935672	bi
2300	14	10	405.6569454	467.4528782	522.4845671	2	541.5071652	bi
2300	14	10	571.434376	533.4956447	471.8471809	3	471.0027912	bi
2300	14	10	477.7944604	567.9803524	606.428315	4	435.2872213	bi
2300	14	10	617.4249668	586.7074246	507.1925189	5	416.1807741	bi
2300	14	10	498.0029535	598.7759478	628.9373119	6	403.8359332	bi
2300	14	10	633.6009213	606.864945	519.7457888	7	395.7399333	bi
2300	14	10	506.2298176	613.5417307	640.4629072	8	389.047762	bi
2300	14	10	643.3461173	618.7676045	526.2423138	9	383.7979786	bi
2300	14	1	511.3134071	623.9238917	648.7619587	10	378.7146903	bi
2100	6	10	323.2327808	323.2627128	323.2639505	1	619.453529	uni
2100	6	10	433.3480676	448.81323	430.6113263	2	502.4109911	uni
2100	6	10	465.406392	489.9120606	460.2232722	3	458.4273522	uni
2100	6	10	477.8022172	507.3032102	471.6280311	4	439.7168481	uni
2100	6	10	484.2837128	516.8464649	477.7255909	5	429.0574816	uni
2100	6	10	488.3796643	523.4198112	481.9531085	6	421.5452473	uni
2100	6	10	491.4747366	528.5891323	485.0835384	7	415.6276042	uni
2100	6	10	494.1545696	532.9885751	487.7500926	8	410.3147345	uni
2100	6	10	496.4446098	537.001382	490.083967	9	405.585848	uni
2100	6	1	498.6112845	540.7305251	492.238852	10	401.5016127	uni
2100	8	10	323.1539667	323.1552616	323.1552622	1	710.4038079	uni
2100	8	10	442.3367936	456.2095809	441.0025234	2	549.7312374	uni
2100	8	10	482.1721478	506.4630185	478.9015259	3	491.8593062	uni
2100	8	10	498.3678266	528.7602608	494.0039746	4	466.1115315	uni
2100	8	10	506.267594	540.4389628	501.4312744	5	452.6799214	uni
2100	8	10	510.7748807	547.6831393	505.8116564	6	443.7849317	uni
2100	8	10	513.8444504	553.0300321	509.0295688	7	437.1846313	uni
2100	8	10	516.3907139	557.4563815	511.5386466	8	431.6965529	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2100	8	10	518.6388306	561.4283406	513.7869273	9	426.9589186	uni
2100	8	1	520.7983585	565.1579068	515.8799682	10	422.7053907	uni
2100	10	10	323.1502358	323.1503074	323.1503085	1	606.1364052	uni
2100	10	10	448.2071664	460.7838936	447.5961655	2	449.2302036	uni
2100	10	10	494.7662832	518.5507929	492.6304945	3	391.0120884	uni
2100	10	10	514.7163168	545.7603856	511.7777752	4	365.4146039	uni
2100	10	10	524.6039719	560.1415396	521.1935624	5	351.1833221	uni
2100	10	10	530.0370073	569.0592207	526.7364511	6	342.0097813	uni
2100	10	10	533.7327151	575.5116771	530.3583226	7	336.1498418	uni
2100	10	10	536.7018144	580.5889796	533.3115183	8	331.1571394	uni
2100	10	10	539.2465516	585.0181332	535.768196	9	327.1407104	uni
2100	10	1	541.7066203	589.1382896	538.0108538	10	323.7071092	uni
2100	12	10	323.1500166	323.1500212	323.1500213	1	688.5804513	uni
2100	12	10	449.1429192	460.4651532	448.9503771	2	529.8056196	uni
2100	12	10	498.8802586	521.2557705	497.6299169	3	464.3044058	uni
2100	12	10	521.0785073	551.02906	519.0513346	4	433.8136757	uni
2100	12	10	532.2057909	567.2065966	529.7182334	5	411.7717084	uni
2100	12	10	538.6494531	578.0708278	536.6190489	6	400.5181992	uni
2100	12	10	543.1005256	585.5758079	541.0495134	7	393.1329621	uni
2100	12	10	546.543921	591.3600691	544.3931952	8	387.7051482	uni
2100	12	10	549.5188731	596.2624416	547.2169914	9	382.8509887	uni
2100	12	1	552.2345196	600.7228343	549.7800125	10	378.8171828	uni
2100	14	10	323.1500014	323.1500018	323.1500018	1	626.1049461	uni
2100	14	10	449.9047837	460.1624498	449.8750061	2	481.2756961	uni
2100	14	10	503.2807567	524.7166501	502.5653598	3	424.2773485	uni
2100	14	10	528.0303101	557.4198095	526.6913894	4	397.6202832	uni
2100	14	10	540.7320678	575.4168092	538.7496553	5	382.8577683	uni
2100	14	10	547.9189969	586.5234899	545.8093821	6	373.7010146	uni
2100	14	10	552.84181	594.2576268	550.5134118	7	367.5968452	uni
2100	14	10	556.352883	600.2449533	554.1176842	8	362.9432806	uni
2100	14	10	559.3315163	605.2957879	557.0243876	9	358.8655509	uni
2100	14	1	562.1724649	609.9252523	559.5602815	10	355.2098114	uni
2300	8	10	323.1542636	323.1556402	323.1556411	1	549.9674262	uni
2300	8	10	448.9950362	463.6930393	447.5586639	2	399.3210947	uni
2300	8	10	491.9082057	518.0623199	488.465806	3	345.8849138	uni
2300	8	10	509.6316293	542.4949506	505.0300527	4	322.305247	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2300	8	10	518.3423536	555.4325535	513.2112518	5	309.5095295	uni
2300	8	10	523.4233714	563.5774599	518.0698225	6	300.4638532	uni
2300	8	10	526.9307478	569.6994975	521.5441698	7	294.4274031	uni
2300	8	10	529.7410187	574.6054884	524.305517	8	289.5990201	uni
2300	8	10	532.1565079	578.9143026	526.7534956	9	285.4869582	uni
2300	8	1	534.4207072	582.9029062	529.0372024	10	281.9109754	uni
2300	6	10	296.2210289	296.2463336	296.2472769	1	536.419622	uni
2300	6	10	411.215876	427.3109568	408.3224177	2	406.3634657	uni
2300	6	10	445.238349	470.9684193	439.822021	3	364.6455297	uni
2300	6	10	458.5176328	489.7308242	452.0272905	4	345.3935828	uni
2300	6	10	465.4356036	500.1815194	458.5449392	5	334.4542513	uni
2300	6	10	469.8943229	507.2380048	462.9349478	6	326.7257177	uni
2300	6	10	473.2286049	512.7630582	466.2349939	7	320.5593822	uni
2300	6	10	475.9681848	517.4662749	469.0568558	8	315.4124094	uni
2300	6	10	478.3912083	521.6838949	471.5072193	9	310.6910093	uni
2300	6	1	480.6254765	525.6452605	473.7780408	10	306.5713232	uni
2300	10	10	296.1501828	296.1502386	296.1502387	1	593.6371975	uni
2300	10	10	425.0316925	437.9270879	424.3641974	2	435.083343	uni
2300	10	10	473.6506045	498.2877302	471.4865445	3	422.9637246	uni
2300	10	10	494.5848127	526.750206	491.4935076	4	373.6327806	uni
2300	10	10	504.6718953	541.826935	500.9940731	5	351.2604288	uni
2300	10	10	510.4528951	551.0516357	506.6267042	6	339.2196684	uni
2300	10	10	514.3894171	557.5616214	510.4854845	7	331.8022707	uni
2300	10	10	517.3823061	562.7905423	513.2398113	8	326.4656841	uni
2300	10	10	520.0792124	567.3712542	515.965209	9	322.3522657	uni
2300	10	1	522.4471245	571.63658	518.2299855	10	320.5933702	uni
2300	12	10	296.1500125	296.1500161	296.1500166	1	594.9209861	uni
2300	12	10	427.2332808	438.8090693	426.8530848	2	442.2013096	uni
2300	12	10	479.8227682	503.1550938	478.3677321	3	382.8350593	uni
2300	12	10	503.6648902	535.2418129	501.3486917	4	355.1184543	uni
2300	12	10	515.7113623	552.8364988	512.8951562	5	340.5417194	uni
2300	12	10	522.5620855	563.6422439	519.3882379	6	331.9516098	uni
2300	12	10	527.1400362	571.1240026	523.8677088	7	325.9518283	uni
2300	12	10	530.6675213	577.009932	527.2670927	8	321.3808199	uni
2300	12	10	533.655987	582.0481732	530.2659246	9	317.4642309	uni
2300	12	1	536.3804861	586.6655328	532.9756048	10	313.9129786	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2300	14	10	296.150001	296.1500013	296.1500013	1	601.5644887	uni
2300	14	10	427.3470143	437.8838525	427.2945331	2	461.3236892	uni
2300	14	10	482.2625437	504.2903611	481.5096117	3	403.6907944	uni
2300	14	10	507.9693092	538.3982115	506.285773	4	375.9953438	uni
2300	14	10	521.3037065	557.4280781	519.2377964	5	360.8560304	uni
2300	14	10	528.8398341	569.2409462	526.6584477	6	351.6678779	uni
2300	14	10	533.9182558	577.4944831	531.4948797	7	345.1758941	uni
2300	14	10	537.8643577	583.9364286	535.4560313	8	340.281426	uni
2300	14	10	541.1311667	589.4025368	538.3855465	9	336.2131976	uni
2300	14	1	544.2066404	594.322952	541.4947527	10	332.551598	uni
2000	10	2	296.1507412	296.1509889	296.1509855	1	1105.352864	uni
2000	10	2	443.6599842	454.8667414	436.7500684	2	989.6259396	uni
2000	10	2	511.1658364	534.2647966	499.2398798	3	913.3305218	uni
2000	10	2	545.2791765	577.371207	529.9420464	4	876.379041	uni
2000	10	2	563.784757	602.549709	546.2331982	5	855.1955134	uni
2000	10	2	575.1081555	618.5765363	556.2311307	6	841.7607988	uni
2000	15	2	296.1500027	296.1500036	296.1500036	1	835.888392	uni
2000	15	2	432.2413306	440.650681	428.5058382	2	793.6569684	uni
2000	15	2	506.1762852	522.6829057	497.3490027	3	767.6071004	uni
2000	15	2	549.4144375	574.0158716	537.2404874	4	761.9890825	uni
2000	15	2	576.0910309	608.0650694	561.6058059	5	747.4080576	uni
2000	15	2	593.8853431	631.4074567	577.5829827	6	737.6381915	uni
2000	8	2	296.1591019	296.1623457	296.1623566	1	1074.206838	uni
2000	8	2	444.1557534	457.9718888	436.1131955	2	940.2031348	uni
2000	8	2	504.1302749	530.3399026	490.4172423	3	868.4247739	uni
2000	8	2	531.6269351	566.2596234	514.6976629	4	834.3099594	uni
2000	8	2	545.5884332	585.9088105	526.8587642	5	816.1174947	uni
2000	8	2	553.6989412	597.9449161	533.7309186	6	805.0551785	uni
2000	8	2	296.1591019	296.1623457	296.1623566	1	1074.206838	bi
2000	8	2	365.98041	468.3599653	696.6945977	2	924.110987	bi
2000	8	2	752.8773636	540.3574762	427.6272048	3	857.008284	bi
2000	8	2	443.9204394	578.5996085	804.4617594	4	821.9099797	bi
2000	8	2	820.153912	598.4673219	460.4070658	5	802.9942604	bi
2000	8	2	466.713109	612.1177063	835.7032113	6	790.8997754	bi
2000	6	2	296.2814312	296.3320225	296.3323407	1	949.6661052	uni
2000	6	2	436.8870458	453.7422666	426.7575358	2	826.2373673	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2000	6	2	484.4126727	512.8137252	468.3562796	3	773.2605539	uni
2000	6	2	503.8572159	538.9794707	484.9212955	4	750.6906421	uni
2000	6	2	513.3352815	552.6023733	493.0873254	5	738.6586675	uni
2000	6	2	518.8458075	561.1564315	497.9125594	6	730.8083872	uni
2000	6	2	296.2814312	296.3320225	296.3323407	1	949.6661052	bi
2000	6	2	349.870414	467.857962	742.0717747	2	806.9086791	bi
2000	6	2	781.7651207	525.3985278	397.9120583	3	758.8489512	bi
2000	6	2	409.831034	553.0242744	818.6765535	4	735.5405234	bi
2000	6	2	829.5253362	566.2872671	421.7915425	5	723.8485151	bi
2000	6	2	427.694471	575.7959043	839.8967607	6	715.5944862	bi
2000	12	2	296.1500678	296.1500896	296.1500897	1	1112.775742	uni
2000	12	2	440.437488	449.5628581	434.2856814	2	979.9185175	uni
2000	12	2	511.8417803	531.6535906	501.0780065	3	913.0588521	uni
2000	12	2	550.4414759	579.4020584	536.2158576	4	882.9386935	uni
2000	12	2	572.9531364	608.8677667	556.6295199	5	861.4420822	uni
2000	12	2	587.0282723	628.3986597	568.9880392	6	846.8116984	uni
2000	12	2	296.1500678	296.1500896	296.1500897	1	1112.775742	bi
2000	12	2	380.3148151	458.6597864	635.0158452	2	971.3767959	bi
2000	12	2	705.0705006	541.4111741	452.6897008	3	905.8801297	bi
2000	12	2	476.1946981	590.9760386	766.6273734	4	870.0799336	bi
2000	12	2	788.9526422	620.8305058	500.0198524	5	847.9996496	bi
2000	12	2	508.30813	641.3824423	811.0498529	6	831.5343123	bi
2000	14	2	296.1500074	296.1500095	296.1500095	1	946.2194614	uni
2000	14	2	435.8515607	443.453703	430.3067453	2	877.6882881	uni
2000	14	2	508.9393102	526.1059673	498.7933445	3	860.7465774	uni
2000	14	2	550.8730618	576.7410137	537.8740462	4	827.2562259	uni
2000	14	2	576.4215757	609.245929	560.9847663	5	811.0889887	uni
2000	14	2	592.9568138	631.5683929	575.8449476	6	794.3927021	uni
2000	14	2	296.1500074	296.1500095	296.1500095	1	946.2194614	bi
2000	14	2	382.4266466	452.6161668	611.4583687	2	878.5397681	bi
2000	14	2	682.2901886	535.4972509	455.4074712	3	850.4250181	bi
2000	14	2	481.8169428	587.6249178	744.7783563	4	818.6661781	bi
2000	14	2	768.9190317	620.241521	507.7862104	5	797.6184095	bi
2000	14	2	517.6958217	643.2812008	792.777354	6	782.475612	bi
2100	14	20	296.15	296.15	296.15	1	1040.480831	uni
2000	6	2	296.2814312	296.3320225	296.3323407	1		bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2000	6	2	349.870414	467.857962	742.0717747	2		bi
2000	6	2	781.7651207	525.3985278	397.9120583	3		bi
2000	6	2	409.831034	553.0242744	818.6765535	4		bi
2000	10	10	296.1507412	296.1509889	296.1509855	1	347.9710897	bi
2000	10	10	351.2598422	413.618599	478.2962208	2	270.0541449	bi
2000	10	10	506.0144487	456.3902682	387.0579529	3	244.7271917	bi
2000	10	10	397.381752	476.2751488	525.5362272	4	233.6055987	bi
2000	10	10	530.2068372	486.2827101	406.0061427	5	227.8749526	bi
2000	10	1	410.2336658	493.0832941	535.8109063	6	224.1521161	bi
2400	6	2	296.3037993	296.3628891	296.363313	1		bi
2400	6	2	357.2931997	491.5176318	801.4980935	2		bi
2400	6	2	856.6153002	561.7119662	413.7327621	3		bi
2400	6	2	428.4871187	595.0107228	900.4924214	4		bi
2400	6	2	296.3037993	296.3628891	296.363313	1	984.2793223	uni
2400	6	2	456.26236	475.5212213	444.7179285	2	826.7195324	uni
2400	6	2	514.128549	547.3960863	495.6561717	3	763.763638	uni
2400	6	2	537.6493484	578.8953258	515.7523127	4	736.7351952	uni
2400	6	2	548.9628593	595.1136345	525.4296642	5	721.9816918	uni
2400	6	2	555.4015163	605.1007791	531.0594945	6	712.2038529	uni
2400	8	2	296.1607218	296.1645246	296.1645374	1	1143.60321	uni
2400	8	2	465.1831562	480.9533048	455.9230693	2	964.1385552	uni
2400	8	2	534.9888443	565.1917225	519.1418745	3	873.3802078	uni
2400	8	2	567.2271633	607.3072309	547.5941072	4	831.1801168	uni
2400	8	2	583.6540567	630.3669687	561.9213856	5	808.3410115	uni
2400	8	2	593.1521036	644.4307099	569.9155697	6	794.4629967	uni
2400	8	2	296.1607218	296.1645246	296.1645374	1	1143.60321	bi
2400	8	2	375.9393498	492.6754411	751.6022463	2	945.4406928	bi
2400	8	2	816.9463494	576.384819	447.2061347	3	860.7545879	bi
2400	8	2	466.187001	621.1218414	877.0709747	4	816.6025796	bi
2400	8	2	895.7801801	644.3993976	485.4493133	5	793.0633707	bi
2400	8	2	492.8022526	660.3053173	914.0383672	6	777.8903547	bi
2400	10	2	296.1508779	296.1511699	296.1511658	1	1241.626014	uni
2400	10	2	465.4016663	478.190385	457.36184	2	1054.433606	uni
2400	10	2	544.1705713	570.8948756	530.2515356	3	950.2874004	uni
2400	10	2	584.2091951	621.6514713	566.47971	4	898.6640328	uni
2400	10	2	606.1181034	651.4071469	585.768007	5	868.7962	uni

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2400	10	2	619.4854541	670.2807499	597.5118457	6	850.0596747	uni
2400	10	2	296.1508779	296.1511699	296.1511658	1	1241.626014	bi
2400	10	2	386.992536	488.7588512	714.9059473	2	1039.43222	bi
2400	10	2	790.9004367	581.4850522	467.1710287	3	938.45564	bi
2400	10	2	491.0263635	634.9518552	860.3170014	4	883.4387305	bi
2400	10	2	883.7006238	665.1489335	515.0813869	5	852.2774714	bi
2400	10	2	523.7138773	685.7365094	906.4748044	6	831.3707844	bi
2400	12	2	296.1500807	296.1501066	296.1501067	1	1298.373413	uni
2400	12	2	462.1483473	472.589232	454.9820594	2	1104.674561	uni
2400	12	2	545.9407756	569.1265241	533.3932065	3	1007.222078	uni
2400	12	2	591.5651581	625.5440322	575.0338375	4	952.1660811	uni
2400	12	2	618.2430692	660.4875532	599.2989097	5	915.0370759	uni
2400	12	2	634.9841204	683.6571907	613.8894554	6	889.7395015	uni
2400	12	2	296.1500807	296.1501066	296.1501067	1	1298.373413	bi
2400	12	2	393.0766121	482.9296631	684.7195952	2	1093.719603	bi
2400	12	2	767.0760615	579.9520789	477.5260161	3	993.9070668	bi
2400	12	2	505.3026002	638.4562585	839.8110045	4	933.8933181	bi
2400	12	2	866.3520961	673.8594298	533.6141042	5	896.5545365	bi
2400	12	2	543.4630595	698.203654	892.5053388	6	871.0186711	bi
2400	14	2	296.1500088	296.1500114	296.1500114	1	1275.920213	uni
2400	14	2	457.6001723	466.2973131	451.0911039	2	1128.089812	uni
2400	14	2	543.3116661	563.4302134	531.5969559	3	1041.229205	uni
2400	14	2	593.0412027	623.4722755	577.8777274	4	975.2843227	uni
2400	14	2	623.4366103	662.2794496	605.557739	5	932.2177359	uni
2400	14	2	643.091889	688.7430107	623.2744802	6	903.2121994	uni
2400	14	2	296.1500088	296.1500114	296.1500114	1	1275.920213	bi
2400	14	2	395.9900701	476.7886469	659.5002464	2	1116.022385	bi
2400	14	2	743.1428329	574.293286	481.3991758	3	1024.899207	bi
2400	14	2	512.8604947	635.9982389	816.8515531	4	959.6732897	bi
2400	14	2	845.7638669	674.9106099	543.7519304	5	917.6864982	bi
2400	14	2	555.5823154	702.3383128	873.9914808	6	889.4252455	bi
2200	8	2	296.1600815	296.1636986	296.1637149	1		bi
2200	8	2	370.9117522	480.4519351	724.0055345	2		bi
2200	8	2	785.3454672	558.5009351	437.4503127	3		bi
2200	8	2	455.1351421	599.9750418	841.6234433	4		bi
2200	8	2	858.3761744	621.4409467	473.0124386	5		bi

Continued on next page

Table E.1: – *Continued from previous page*

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	8	2	479.7708525	636.1869387	875.4693961	6		bi
2200	6	2	296.2927904	296.3476543	296.3479857	1	978.375211	uni
2200	6	2	446.6977551	464.6812268	435.7769494	2	825.0706544	uni
2200	6	2	498.1741313	528.6378266	480.8680061	3	771.9247635	uni
2200	6	2	519.092108	556.7886979	498.710974	4	747.028542	uni
2200	6	2	529.3679545	571.6841282	507.497465	5	732.9156579	uni
2200	6	2	535.3110074	580.9890754	512.7191982	6	723.7360374	uni
2200	8	2	296.1599157	296.1634436	296.1634574	1	1128.269764	uni
2200	8	2	454.7531456	469.5680797	446.1125558	2	949.8756462	uni
2200	8	2	519.9115166	548.2046942	505.1472271	3	879.0104922	uni
2200	8	2	549.7694552	587.0635769	531.4821311	4	841.899958	uni
2200	8	2	564.8429357	608.3203613	544.6512088	5	820.4220136	uni
2200	8	2	573.6488078	621.4187303	552.0445317	6	806.8691587	uni
2200	10	2	296.15081	296.15108	296.1510763	1	1196.712631	uni
2200	10	2	454.8240733	466.8602457	447.4185122	2	1026.856065	uni
2200	10	2	527.993319	552.8562091	515.0189194	3	948.4999519	uni
2200	10	2	565.0277995	599.7269219	548.3668703	4	900.3112952	uni
2200	10	2	585.1686342	627.2009864	566.1284658	5	871.4832248	uni
2200	10	2	597.5059814	644.7487035	577.0387194	6	852.5240901	uni
2200	10	2	296.15081	296.15108	296.1510763	1	1196.712631	bi
2200	10	2	381.2890844	476.8546565	689.7430977	2	1015.029966	bi
2200	10	2	760.7919302	563.0436232	456.0377622	3	933.4720818	bi
2200	10	2	478.2172851	612.4137892	824.1888786	4	884.049278	bi
2200	10	2	845.7288118	640.2917686	500.2091705	5	855.5927865	bi
2200	10	2	508.2587464	659.3287062	866.4599036	6	836.6117941	bi
2200	12	2	296.1500743	296.1500981	296.1500982	1	1188.899967	uni
2200	12	2	451.5334206	461.3620465	444.9317472	2	1064.618244	uni
2200	12	2	529.1568655	550.7543844	517.4866564	3	982.0429885	uni
2200	12	2	571.3676301	602.9881974	555.9900897	4	927.3196104	uni
2200	12	2	596.1654308	635.3870004	578.486251	5	895.5240361	uni
2200	12	2	611.617905	656.7981611	592.0219256	6	875.436291	uni
2200	12	2	296.1500743	296.1500981	296.1500982	1	1188.899967	bi
2200	12	2	386.83774	471.1068008	660.6847025	2	1051.657172	bi
2200	12	2	736.3335933	561.0053986	465.3882291	3	968.3606033	bi
2200	12	2	490.9392255	615.2188833	803.8092603	4	915.0651119	bi
2200	12	2	828.2087463	647.9884674	517.0637246	5	882.7751665	bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	12	2	526.1186656	670.4644894	852.5626209	6	861.6150576	bi
2200	14	2	296.1500081	296.1500105	296.1500105	1	1154.034796	uni
2200	14	2	446.8368036	454.8319929	440.6569462	2	1047.949235	uni
2200	14	2	526.3846389	545.0820175	515.4422674	3	964.5076176	uni
2200	14	2	572.1811052	600.355189	558.0897975	4	923.4378379	uni
2200	14	2	600.2571723	636.1062543	583.4834461	5	896.9509538	uni
2200	14	2	618.3641095	660.4600268	599.7473254	6	876.9171743	uni
2200	14	2	296.1500081	296.1500105	296.1500105	1	1154.034796	bi
2200	14	2	389.2783981	464.6482051	635.39656	2	1034.390167	bi
2200	14	2	713.5457553	555.086716	468.3889004	3	956.0075876	bi
2200	14	2	497.5469991	612.0609002	781.3772189	4	910.3552748	bi
2200	14	2	807.9401678	647.8218175	525.9448417	5	882.1421852	bi
2200	14	2	536.9252441	673.0827126	834.0137614	6	860.737	bi
2200	14	25	296.1500081	296.1500105	296.1500105	1	1154.034796	uni
2200	6		346.1044053	342.7669903	323.2677703	2	934.3884283	uni
2000	14	50	296.1500074	296.1500095	296.1500095	1	946.2194614	uni
2000	12	0	311.7947389	315.3743255	309.2103547	2	1099.488873	uni
2200	6	2	296.2927904	296.3476543	296.3479857	1		bi
2200	6	2	353.6280693	479.7605341	771.9108876	2		bi
2200	6	2	823.3159109	545.449166	406.7593019	3		bi
2200	6	2	420.5074741	577.2972132	864.4894547	4		bi
2200	10	4	296.15081	296.15108	296.1510763	1	295.6390296	bi
2200	10	4	373.9029596	459.8867841	597.7930883	2	205.4428483	bi
2200	10	4	655.4818514	533.4198725	437.4090439	3	174.1225886	bi
2200	10	4	455.7703734	573.1801312	705.5988858	4	159.0261557	bi
2200	10	4	721.7442162	594.7471548	473.0978402	5	150.9490577	bi
2200	10	1	479.7445564	609.2546717	738.0504616	6	145.8979375	bi
2200	12	4	296.1500743	296.1500981	296.1500982	1	351.2596945	bi
2200	12	4	378.8899207	453.3751828	570.1380957	2	256.5117722	bi
2200	12	4	632.7279415	529.9349399	445.5615536	3	217.1010117	bi
2200	12	4	466.2860926	573.4269767	686.3513222	4	196.8902548	bi
2200	12	4	705.1266527	598.5574947	486.3218314	5	185.7769485	bi
2200	12	1	493.3569755	615.4363454	723.6921235	6	178.8137313	bi
2200	14	4	296.1500081	296.1500105	296.1500105	1	416.9192324	bi
2200	14	4	381.0324644	446.2150827	547.1257399	2	313.588687	bi
2200	14	4	612.4984567	523.2254561	448.0299011	3	267.4019359	bi

Continued on next page

Table E.1: – *Continued from previous page*

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	14	4	471.3795879	568.8104458	666.8462353	4	243.3691564	bi
2200	14	4	687.4557755	596.1334056	492.8363508	5	229.688006	bi
2200	14	1	500.9235598	614.8687778	707.3473369	6	221.014911	bi
2400	8	4	296.1607218	296.1645246	296.1645374	1	209.6958736	bi
2400	8	4	369.1020028	475.558515	654.2178046	2	138.2146947	bi
2400	8	4	705.8738961	547.1781847	429.8934473	3	116.2053226	bi
2400	8	4	446.0570104	583.5277839	752.2885188	4	106.5283933	bi
2400	8	4	765.5810066	601.9081419	461.651796	5	101.5850447	bi
2400	8	1	468.1566864	614.4397651	779.9904004	6	98.49060219	bi
2400	10	4	296.1508779	296.1511699	296.1511658	1	255.7967101	bi
2400	10	4	379.1105402	470.7123877	617.0845791	2	174.5377408	bi
2400	10	4	678.9947491	549.8618572	447.328799	3	145.460663	bi
2400	10	4	467.0767253	592.9736165	733.4185536	4	131.8610496	bi
2400	10	4	750.8887347	616.3340755	485.8655429	5	124.6236527	bi
2400	10	1	493.0202883	632.0087566	768.6306806	6	120.1752112	bi
2400	12	4	296.1500807	296.1501066	296.1501067	1	306.6764605	bi
2400	12	4	384.5812839	464.0442352	588.2009201	2	215.300718	bi
2400	12	4	656.190758	546.7218853	456.2589341	3	180.1637691	bi
2400	12	4	478.8117106	593.7361012	713.8515255	4	162.8987337	bi
2400	12	4	734.2545609	620.8827139	500.5207639	5	153.2793627	bi
2400	12	1	508.1663699	639.1039715	754.4083964	6	147.1704431	bi
2400	14	4	296.1500088	296.1500114	296.1500114	1	358.3166666	bi
2400	14	4	387.1509543	457.0688627	564.9043625	2	263.7495466	bi
2400	14	4	634.8980374	540.0639695	459.4466001	3	222.7190955	bi
2400	14	4	484.6561646	589.4161786	693.6964379	4	200.1703153	bi
2400	14	4	716.166061	619.1699631	507.9992901	5	187.3731271	bi
2400	14	1	516.8044244	639.5693053	737.8253088	6	179.2351748	bi
2000	10	2	296.1507429	296.150992	296.1509886	1	375.6605472	bi
2000	10	2	378.5176931	471.2829094	678.1008675	2	251.7589647	bi
2000	10	2	748.0426475	555.8924212	452.0847531	3	206.7952459	bi
2000	10	2	474.0529194	605.0115236	811.9459558	4	184.3640661	bi
2000	10	2	833.6277999	633.0669011	496.2193388	5	171.9966118	bi
2000	10	2	504.3274667	652.3271155	854.8238074	6	164.2232772	bi
2400	14	10	296.1500088	296.1500114	296.1500114	1	423.0879744	bi
2400	14	10	365.2083476	418.51905	464.2870134	2	346.0097878	bi
2400	14	10	502.1622339	470.2339611	408.7328779	3	300.9336222	bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2400	14	10	422.639034	496.0299347	528.3429312	4	297.3461123	bi
2400	14	10	536.6342145	509.7730466	433.7215152	5	276.2053157	bi
2400	14	10	438.2882438	518.8053977	544.9208849	6	282.4225458	bi
2400	13	2	296.1500264	296.1500344	296.1500346	1	391.1785222	bi
2400	13	2	394.8286454	479.7768936	671.5857916	2	274.8343672	bi
2400	13	2	754.3381622	577.2352759	479.9091955	3	223.1333581	bi
2400	13	2	509.7161929	637.7622271	828.7513456	4	196.2070181	bi
2400	13	2	856.259466	675.0419513	539.303589	5	180.7573199	bi
2400	13	2	550.5074157	701.1303411	884.0008305	6	170.8258157	bi
2400	11	2	296.1502639	296.1503491	296.1503484	1	329.4131485	bi
2400	11	2	390.7308477	486.1990413	699.7576224	2	222.7843758	bi
2400	11	2	779.3685492	581.3649276	473.2628656	3	181.2550811	bi
2400	11	2	499.307011	637.681965	850.6030549	4	159.8658925	bi
2400	11	2	875.1403924	670.7244424	525.6638164	5	147.9116432	bi
2400	11	2	534.7937088	693.5297266	900.3649485	6	140.489814	bi
2400	9	2	296.1529934	296.1540158	296.1540148	1	273.070914	bi
2400	9	2	382.1715806	491.044485	732.2164499	2	177.7565766	bi
2400	9	2	804.2987585	580.2515561	458.829527	3	145.2105337	bi
2400	9	2	480.363259	629.761671	870.0368284	4	129.7785391	bi
2400	9	2	890.7126537	656.703104	502.1737095	5	121.5147922	bi
2400	9	2	509.9461577	675.096194	911.891831	6	116.4442996	bi
2300	6	2	296.2978184	296.3544172	296.3547723	1	208.4881299	bi
2300	6	2	355.4970983	485.7924246	787.2356051	2	127.7945338	bi
2300	6	2	832.2030347	552.5376585	410.1429215	3	107.7695878	bi
2300	6	2	423.6305147	585.0985471	879.0623892	4	99.54701715	bi
2300	6	2	892.6904205	600.6517706	437.6606589	5	95.40985891	bi
2300	6	2	444.3524175	611.53858	905.5857852	6	92.71381225	bi
2300	8	2	296.1603008	296.1639548	296.1639697	1	261.9049409	bi
2300	8	2	373.5163772	486.7716283	738.4080545	2	170.1239904	bi
2300	8	2	802.1115606	567.7426652	442.5127023	3	140.6362244	bi
2300	8	2	460.9143265	610.9192054	860.1787633	4	127.1857725	bi
2300	8	2	877.9926944	633.3746176	479.4840153	5	120.1294506	bi
2300	8	2	486.5672192	648.7814057	895.6266661	6	115.7957251	bi
2200	7	2	296.1868158	296.2003974	296.2004432	1	250.5881772	bi
2200	7	2	363.3815844	481.3468694	746.6087027	2	162.1097676	bi
2200	7	2	799.9158294	552.6037285	423.7171113	3	135.9945061	bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2200	7	2	438.8362289	588.9079713	849.0886739	4	124.6998727	bi
2200	7	2	863.8077648	606.8767105	454.2772283	5	118.8895868	bi
2200	7	2	460.9070361	619.404614	878.0656325	6	115.2485879	bi
2200	9	2	296.1527655	296.1537116	296.1537107	1	312.3343486	bi
2200	9	2	376.8788979	479.1655066	706.2711941	2	208.7323684	bi
2200	9	2	772.8305506	562.0207121	448.3418664	3	172.3150085	bi
2200	9	2	468.2744746	608.0408424	833.8892376	4	155.0743958	bi
2200	9	2	853.1924105	633.0231355	488.5140611	5	145.8962171	bi
2200	9	2	495.728519	650.0749184	872.7991099	6	140.2380079	bi
2200	11	2	296.1502432	296.1503219	296.1503213	1	379.2772583	bi
2200	11	2	384.630202	474.088942	674.5198176	2	262.2238229	bi
2200	11	2	748.6807855	562.6575997	461.4420047	3	215.8746966	bi
2200	11	2	485.5660127	614.8454025	814.932791	4	192.8573262	bi
2200	11	2	837.6415613	645.2715274	509.9925298	5	179.9451998	bi
2200	11	2	518.4184795	666.2796553	860.7818195	6	171.7419356	bi
2200	13	2	296.1500243	296.1500317	296.1500318	1	451.116675	bi
2200	13	2	388.3138503	467.8175925	647.4612309	2	324.1673012	bi
2200	13	2	724.4398092	558.2355982	467.3590461	3	269.9234101	bi
2200	13	2	494.890532	614.0712018	792.7673317	4	239.7573183	bi
2200	13	2	818.3211833	648.3987733	522.0200615	5	221.9631944	bi
2200	13	2	532.3991283	672.4927361	843.4982143	6	210.5585062	bi
2000	7	2	296.1838617	296.1963951	296.1964372	1	293.9604984	bi
2000	7	2	358.8721857	469.0040117	717.3658837	2	193.0491424	bi
2000	7	2	767.0920556	534.9835786	414.8050989	3	164.2551073	bi
2000	7	2	428.8620349	568.3315367	812.5390003	4	151.5000688	bi
2000	7	2	826.0917583	584.8409713	443.1026195	5	144.9429381	bi
2000	7	2	449.2639653	596.4050871	839.0550332	6	140.7488776	bi
2000	9	2	296.1525358	296.1534058	296.1534046	1	365.7522143	bi
2000	9	2	371.3249298	466.6775182	678.7917844	2	249.8109035	bi
2000	9	2	740.7040075	543.1946782	437.3912762	3	209.7986286	bi
2000	9	2	455.8327808	585.3209236	796.6520572	4	190.4962723	bi
2000	9	2	814.2597639	608.1975514	474.3514991	5	180.1417696	bi
2000	9	2	480.9995718	623.8683599	831.9758265	6	173.6432506	bi
2000	11	2	296.1502223	296.1502944	296.1502938	1	440.1409056	bi
2000	11	2	378.4091564	461.6845727	648.5564299	2	316.6178025	bi
2000	11	2	716.7752267	543.1350656	449.2816565	3	265.6219496	bi

Continued on next page

Table E.1: – Continued from previous page

P_k	v_k	τ	$T_{initial,L,K}$	$T_{init,M,k}$	$T_{init,R,k}$	layer	Cooling Rate	Printing Type
2000	11	2	471.3826046	590.9683347	777.3533995	4	238.7374833	bi
2000	11	2	798.0386193	618.8869594	493.6955363	5	223.6863888	bi
2000	11	2	501.3921821	638.1892869	819.1628745	6	214.2205207	bi
2000	13	2	296.1500221	296.1500289	296.150029	1	524.8346172	bi
2000	13	2	381.5230113	455.3272024	622.2398744	2	392.3817856	bi
2000	13	2	693.3839532	538.526031	454.3942929	3	331.3144873	bi
2000	13	2	479.6389945	589.7545465	756.023723	4	297.9221422	bi
2000	13	2	779.2593008	621.1000044	504.4255591	5	278.3200079	bi
2000	13	2	513.8762404	643.0851491	802.1986756	6	265.7856292	bi

Table E.2: Solidification Cooling Rate Collected by FE model.

$T_{init,M,k}$	CoolingRate	P_k	v_k
296.1500069	1254.73201	2000	12
436.1051878	1122.903566	2000	12
436.8206224	1119.743635	2000	12
436.8201099	1120.48421	2000	12
436.3178768	1121.267364	2000	12
510.464714	990.7486082	2000	12
513.343212	985.838915	2000	12
513.3455763	985.7891544	2000	12
510.8334336	988.1213244	2000	12
553.6346636	936.3518681	2000	12
559.314251	925.948382	2000	12
559.3460896	925.6367032	2000	12
553.9433083	931.1450398	2000	12
580.1011538	906.7734002	2000	12
588.6400748	890.769377	2000	12
588.7058768	890.4700442	2000	12
580.2790068	899.7524036	2000	12
597.6028013	870.1506815	2000	12
608.6286227	833.7086974	2000	12
608.7234822	833.6515076	2000	12
597.5507248	846.3858207	2000	12
296.1500006	1333.851872	2000	14
437.6091407	1148.56446	2000	14

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
438.1423908	1147.212341	2000	14
438.1412231	1147.244715	2000	14
437.7900494	1147.394001	2000	14
517.6321531	1021.710973	2000	14
519.9518202	1017.579529	2000	14
519.9495906	1018.13381	2000	14
517.9991918	1019.113978	2000	14
566.4187231	940.1614945	2000	14
571.2864858	930.1190295	2000	14
571.3030229	930.0954689	2000	14
566.8518055	936.5050289	2000	14
597.6524969	896.8199579	2000	14
605.216945	883.4136865	2000	14
605.2652221	883.6081687	2000	14
597.9639679	891.472672	2000	14
618.6392481	871.1721453	2000	14
628.7642532	855.5374197	2000	14
628.8484547	855.054881	2000	14
618.8410979	865.2754531	2000	14
296.1501046	1244.993421	2000	10
432.0954427	1043.109241	2000	10
433.1091417	1042.28546	2000	10
433.1082166	1041.802502	2000	10
432.3776898	1043.231274	2000	10
499.7433891	961.7271245	2000	10
503.3723841	958.665467	2000	10
503.3913774	958.4646974	2000	10
500.0736366	960.3324756	2000	10
536.7911384	930.3429026	2000	10
543.3413621	919.3303652	2000	10
543.3965286	919.3054742	2000	10
536.9933587	926.7856369	2000	10
557.6361178	901.8900386	2000	10
566.7639811	886.245166	2000	10
566.8483951	886.0011408	2000	10
557.5780208	897.7440259	2000	10

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
570.4783845	884.2397508	2000	10
581.7471365	864.4834682	2000	10
581.8450128	864.0385397	2000	10
570.1737768	879.5041539	2000	10
296.1519513	1194.240464	2000	8
426.3163181	976.6638138	2000	8
427.8491933	974.417323	2000	8
427.8493444	974.4072516	2000	8
426.6808529	975.2105099	2000	8
483.2533004	929.1779739	2000	8
487.7065705	924.3556639	2000	8
487.7421784	924.1618491	2000	8
483.4982108	926.9143321	2000	8
510.4471974	908.8588	2000	8
517.7270648	898.6541376	2000	8
517.8036124	898.3806014	2000	8
510.2903645	905.9236732	2000	8
524.9130252	884.9109152	2000	8
534.5165355	864.7588222	2000	8
534.6055159	864.4441297	2000	8
524.392157	880.2974811	2000	8
533.6491119	869.7641516	2000	8
545.0542711	845.8792936	2000	8
545.1358809	845.4914016	2000	8
532.8554239	865.5312016	2000	8
296.1949489	1054.021812	2000	6
414.0749882	915.6240462	2000	6
416.3860847	913.1886272	2000	6
416.3986899	913.1333407	2000	6
414.4221984	914.2331243	2000	6
456.62666	862.0011119	2000	6
462.0239472	819.3328711	2000	6
462.0941392	819.0631594	2000	6
456.47486	826.6781668	2000	6
475.3141462	809.4203358	2000	6
483.6859588	793.4198491	2000	6

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
483.8316717	793.1850366	2000	6
475.1894572	802.2950015	2000	6
484.8598644	795.6963016	2000	6
494.7392815	782.1725966	2000	6
494.8509662	781.6838303	2000	6
484.1850138	791.2878517	2000	6
490.4780413	788.946615	2000	6
501.5122932	774.916438	2000	6
501.5990415	774.6450973	2000	6
489.4933128	785.0376984	2000	6
296.1949489	1054.021812	2000	6
360.0863556	961.5109935	2000	6
395.2596467	925.3291607	2000	6
444.8540712	845.668398	2000	6
537.1695626	760.579273	2000	6
571.0021364	734.6255952	2000	6
487.3729382	789.7930441	2000	6
444.5173448	841.6449271	2000	6
407.609269	908.414343	2000	6
420.7712853	883.835271	2000	6
463.0761586	815.5441576	2000	6
512.7506567	766.8345726	2000	6
601.2687765	711.1339765	2000	6
608.975121	702.9566459	2000	6
521.6383094	758.5702305	2000	6
475.1430113	799.3881843	2000	6
432.1502153	862.0169024	2000	6
438.3783614	851.290702	2000	6
482.2014494	791.448057	2000	6
528.6946941	753.4494005	2000	6
618.4144684	696.0346925	2000	6
296.1591278	1146.027105	2000	7
370.3449119	1008.28973	2000	7
404.1577189	967.7283168	2000	7
449.7642619	923.9105679	2000	7
537.0737462	824.3616767	2000	7

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
579.5074538	762.4374565	2000	7
499.0953329	868.3065537	2000	7
459.2888926	914.9981201	2000	7
425.3770505	944.2553597	2000	7
442.0305636	928.6752487	2000	7
482.2781846	894.3916158	2000	7
527.9472358	806.2108571	2000	7
615.3360529	736.1362916	2000	7
625.9398449	725.8493154	2000	7
540.4030255	781.7492521	2000	7
497.3426941	870.7754101	2000	7
455.5809416	915.1201963	2000	7
462.3582678	909.3341878	2000	7
506.1868414	851.1260271	2000	7
550.4025039	769.7596907	2000	7
637.5301906	716.9606471	2000	7
296.1504395	1214.601351	2000	9
383.9776042	1029.437807	2000	9
413.7319084	1004.652834	2000	9
452.7987671	973.9604738	2000	9
533.7996094	920.0742216	2000	9
595.1250576	840.4022563	2000	9
517.6346868	928.8887141	2000	9
481.8400895	952.4484305	2000	9
450.8320138	974.3893324	2000	9
474.6831409	956.1867135	2000	9
513.6899303	931.0100293	2000	9
557.042229	872.9332511	2000	9
642.2955741	781.6123214	2000	9
659.3206382	756.6721958	2000	9
576.0569265	842.1844911	2000	9
534.2572333	905.0527489	2000	9
493.8186978	942.7445779	2000	9
502.731119	936.3399406	2000	9
546.1727875	885.6672337	2000	9
590.6544484	823.1498509	2000	9

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
675.8463517	736.405195	2000	9
296.1500263	1260.949675	2000	11
393.4734358	1172.317079	2000	11
420.0518216	1112.183969	2000	11
455.832142	1052.131554	2000	11
534.5601296	953.6220517	2000	11
602.4819517	863.5873572	2000	11
527.8546578	941.080237	2000	11
495.0938644	984.4759843	2000	11
468.2194627	1025.718379	2000	11
497.772856	977.3973107	2000	11
535.2485364	929.5774206	2000	11
576.5222975	877.9267789	2000	11
658.6646715	793.2307552	2000	11
682.3475471	761.4808055	2000	11
603.7358787	841.9658122	2000	11
562.0532695	891.5584932	2000	11
522.4895421	940.9831839	2000	11
534.4793151	924.7896962	2000	11
578.5460674	870.339304	2000	11
623.3491039	817.3731521	2000	11
704.4788592	734.8821183	2000	11
296.1500006	1333.851872	2000	14
437.6091407	1148.56446	2000	14
438.1423908	1147.212341	2000	14
438.1412231	1147.244715	2000	14
437.7900494	1147.394001	2000	14
517.6321531	1021.710973	2000	14
519.9518202	1017.579529	2000	14
519.9495906	1018.13381	2000	14
517.9991918	1019.113978	2000	14
566.4187231	940.1614945	2000	14
571.2864858	930.1190295	2000	14
571.3030229	930.0954689	2000	14
566.8518055	936.5050289	2000	14
597.6524969	896.8199579	2000	14

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
605.216945	883.4136865	2000	14
605.2652221	883.6081687	2000	14
597.9639679	891.472672	2000	14
618.6392481	871.1721453	2000	14
628.7642532	855.5374197	2000	14
628.8484547	855.054881	2000	14
618.8410979	865.2754531	2000	14
296.1998988	1006.214751	2300	6
420.8228464	846.328588	2200	6
423.3173203	843.6697116	2200	6
423.3251929	843.6678895	2200	6
421.2170555	844.4654886	2200	6
464.2152735	793.6069774	2300	6
469.9076132	780.1252114	2300	6
469.9811707	779.7467559	2300	6
464.0933572	789.2148199	2300	6
484.2479873	763.8417454	2300	6
492.5331444	748.3691711	2300	6
492.6380663	747.7180801	2300	6
483.5289452	759.5254009	2300	6
494.13055	748.9387263	2300	6
504.3650133	732.8826238	2300	6
504.4482629	732.5852186	2300	6
493.0132123	744.9369609	2300	6
500.1899038	740.8141014	2300	6
511.8741669	723.8833349	2300	6
511.9286824	723.5480475	2300	6
498.8052747	736.8252318	2300	6
296.1522207	1117.07996	2300	8
432.8000502	948.6647945	2200	8
434.3901933	945.2647836	2200	8
434.3923552	944.5047664	2200	8
433.157039	946.0089969	2200	8
490.5067049	824.9007342	2300	8
495.2361494	816.4870842	2300	8
495.2732116	816.4660628	2300	8

Continued on next page

Table E.2: – *Continued from previous page*

$T_{init,M,k}$	CoolingRate	P_k	v_k
490.7306069	820.2978759	2300	8
522.7211971	791.8781776	2300	8
530.6830172	782.4203325	2300	8
530.7672678	782.2440154	2300	8
522.6842825	788.5987083	2300	8
539.4372023	776.9603564	2300	8
549.8722778	765.8063826	2300	8
549.9805022	765.5417567	2300	8
539.0197415	773.5903072	2300	8
549.1829098	768.7484079	2300	8
561.5287536	756.3950695	2300	8
561.6310266	756.1631566	2300	8
548.466225	765.3196918	2300	8
296.1501196	1152.337711	2300	10
296.1501241	1145.687497	2400	10
442.2145274	967.7768123	2300	10
443.3052696	964.6518839	2300	10
443.3050907	964.4727382	2300	10
442.5005479	966.1681865	2300	10
512.4393959	855.7112519	2400	10
516.3003712	845.1735889	2400	10
516.3201766	845.3430929	2400	10
512.7617918	850.2605116	2400	10
552.8660978	798.5918249	2400	10
560.0710589	785.9305694	2400	10
560.1329184	785.8801177	2400	10
552.9820758	792.5431397	2400	10
576.4081054	766.6169063	2400	10
586.6025098	735.4798064	2400	10
586.7044696	734.6871329	2400	10