Mesoscale Modeling of Stress and Strain Evolution in Electron Beam Powder Bed Fusion Additive Manufacturing (EB-PBF)

by

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Mesoscale Modeling of Stress and Strain Evolution in Electron Beam Powder Bed Fusion Additive Manufacturing (EB-PBF)

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Abstract

Components manufactured using the Electron Beam Powder Bed Fusion (EB-PBF) Additive Manufacturing method are often prone to deformation and residual stress caused by the repeated heating, melting, solidification, and cooling that occurs during the process. The presence of residual stress can reduce the service life of the parts. An estimation of the magnitude, state, and distribution of residual stress can aid in maintaining the dimensional accuracy of the component. Although effort has been made to understand the residual stress development in EB-PBF, understanding the complicated interaction between a newly deposited powder layer and the consolidated layer is still in its infancy.

In this study, a coupled thermomechanical model was built to examine the buildup of stress and inelastic strain during the layer-by-layer processing of a part at the mesoscale level. A small mesoscale domain was developed to represent a volume extracted from within a much larger component. The sub-domain dimensions were chosen to include the total thickness of four powder layers and a section of previously deposited material equivalent to approximately eight consolidated layers. The model uses a novel approach to capture the transition in material response when the material changes from powder to liquid to solid. A user-defined subroutine was developed to correctly describe the evolution of thermal strain as the material solidifies and contracts.

The mesoscale model developed in this work has been used to examine different scenarios. The effect of substrate temperature, electron beam power, and scan speed on the residual stress and deformation were examined. The numerical results show that a compressive plastic strain field forms in proximity to the melt pool. The model also indicates that within the temperature range of 630 °C to 730 °C, a 50 °C increase in substrate temperature leads to a ~21% decrease in the inelastic strain magnitude. Within the beam power range of 740 W to 940 W, the in-elastic strain decreased by ~9% with a 100 W increase in the beam power; and a ~23% increase in the in-elastic strain was observed with a 200 mm s⁻¹ increase in the beam speed.
Lay Summary

The following work presents a mesoscale model to predict strain accumulation around the melt pool region in Electron Beam Powder Bed Fusion of Ti-6Al-4V alloy. EB-PBF has gained attention in industries due to its advantages over the conventional manufacturing processes in producing critical parts. However, the application of a rapidly moving high-intensity heat input, i.e., the Electron Beam (EB), leads to recurrent heating and cooling cycles in a component. One of the consequences of this is the development of large in-situ distortion and residual stresses that hamper the service life of the component. The goal of this work is to estimate the inelastic strain accumulated around the melt pool. The mesoscale model can be run over a range of process conditions to produce a look-up table of “average plastic strains” that may be implemented into a macroscale finite element (FE) model or Reduced Order Model (ROM) thermal-stress analysis.
Preface

This thesis is the original, independent research work that I had done to examine the mesoscale modeling of strain evolution in Electron Beam Powder Bed Fusion Additive Manufacturing (EB-PBF) of Ti6Al4V alloy. To complete this research work, I have completed the following steps:

1. I developed a mesoscale thermal stress Finite Element (FE) model to measure the strain accumulation around the melt pool in PB-EBAM of Ti6Al4V alloy. My supervisors Dr. Cockcroft, Dr. Maijer, and Dr. Farhang Mehr provided continuing support and guidance in every aspect of the model development, discussion of the results, and editing of the thesis.

2. My colleague Pegah Pourabdollah, a Ph.D. Graduate Research Assistant in the “Advanced Materials Processing Group” has provided me with her valuable feedback and support in writing the user-defined subroutines and the technical discussions on mathematical modeling.

3. I have run the models on different case scenarios to study the effect of processing parameters like the beam power, speed, and substrate temperature on the analysis.
# Table of Contents

Abstract.................................................................................................................................................. iii

Lay Summary ........................................................................................................................................ iv

Preface.................................................................................................................................................... v

Table of Contents ................................................................................................................................. vi

List of Tables ......................................................................................................................................... ix

List of Figures ....................................................................................................................................... x

List of Symbols ..................................................................................................................................... xiv

Acknowledgments ............................................................................................................................... xvi

Chapter 1: Introduction ........................................................................................................................ 1

1.1 Classification of the Metal Additive Manufacturing Processes............................................... 2

1.2 Electron Beam Powder Bed Fusion (EB-PBF) Technology....................................................... 3

1.3 Advantages and drawbacks of the EB-PBF process ................................................................. 4

1.4 Defects in EB-PBF produced parts ............................................................................................ 5

1.5 Motivation....................................................................................................................................... 6

Chapter 2: Literature Review .............................................................................................................. 7

2.1 Distortion and residual stress evolution in EB-PBF ................................................................. 7

2.2 Experimental Characterization of Residual Stress and Distortion in the PBF process .......... 8

2.3 Modeling Methodology of residual stress in AM ........................................................................ 10

2.3.1 Heat Transport Phenomena in EB-PBF .............................................................................. 11

2.3.2 Descriptions of PBF Heat Sources....................................................................................... 14

2.3.3 Latest Research in Modeling and Validation of Residual Stress ......................................... 14

2.4 Summary....................................................................................................................................... 22
Chapter 3: Scope and Objective of the Research..........................23

Chapter 4: Three-Dimensional Model Development..........................24

4.1 Modeling Methodology .................................................................24

4.1.1 Governing Equations ...............................................................24

4.1.2 Computational Domain ............................................................24

4.1.3 Mesh .........................................................................................26

4.1.4 User-Defined Subroutines .........................................................27

4.1.4.1 DFLUX subroutine ...............................................................27

4.1.4.2 USDFLD subroutine .............................................................27

4.1.4.3 UEXPAN subroutine .............................................................27

4.1.5 Material Properties .................................................................27

4.1.6 Initial Conditions .......................................................................33

4.1.7 Thermal Boundary Conditions ..................................................33

4.1.7.1 Heat Source Definition ..........................................................35

4.1.8 Mechanical Boundary Conditions .............................................36

4.1.9 Analysis Configuration .............................................................37

Chapter 5: Results and Discussion ..................................................39

5.1 Model Validation ...........................................................................39

5.2 Discussion .....................................................................................41

5.3 Effect of Parameters .....................................................................55

5.3.1 Substrate Temperature ............................................................55

5.3.2 Change of Beam Power ...........................................................57

5.3.3 Beam Speed ..............................................................................59
Chapter 6: Conclusion and future scope of work .................................................................63

6.1 Summary ................................................................................................................................. 63

6.2 Scope of future work ............................................................................................................... 64

References ..................................................................................................................................65

Appendix .....................................................................................................................................73
List of Tables

Table 1.1. Common metals and alloys used in additive manufacturing applications [4], [5] ....... 2
Table 2.1. Different heat source models used in the literature [29]................................. 14
Table 2.2. Comparison of the L-PBF and EB-PBF process parameters [1], [34]................. 15
Table 4.1. Mesh statistics................................................................................................. 26
Table 4.2. Beam Parameters ....................................................................................... 36
Table 4.3. Steps defined for the first layer.................................................................... 38
Table 4.4. Time step values ......................................................................................... 38
Table 5.1. A look-up table showing the effect of different processing conditions on the magnitude of the plastic strain after cooling the deposited layers to the substrate temperature... 61
List of Figures

Figure 1.1. Annual expenditures on part production by AM worldwide in millions of dollars ($M) [3] .................................................................................................................................................. 1

Figure 1.2. (a) 3D printed turbine blades [4] and (b) Titanium skull implant [1] ......................... 2

Figure 1.3. Schematic diagram of an EB-PBF process [7] .................................................................... 4

Figure 1.4. Classification of AM defects ............................................................................................... 5

Figure 2.1. Schematic diagram of residual stress evolution: (a) heating-phase, (b) cooling-phase
[Here, $\varepsilon_{th}$ is the thermal strain, $\varepsilon_{pl}$ is the plastic strain, $\sigma_{tens}$ is tensile stress, $\sigma_{comp}$ is compressive stress, $\sigma_y$ is yield stress, $\sigma_{res}$ is residual stress [19] ................................................................. 8

Figure 2.2. (a)-(b) Experimental results of AM part showing warping; and (c)-(d) Corresponding modeling result [23] ........................................................................................................................................... 9

Figure 2.3. Schematic highlighting the physical phenomena occurring as an electron beam melts a layer of metal powder.................................................................................................................. 12

Figure 2.4. Flowchart of a thermomechanical model of a component produced via PBF [37] .... 16

Figure 2.5. Laser scan strategies used in L-PBF process: a) unidirectional and b) alternating [40] ..................................................................................................................................................... 18

Figure 2.6. Variation of the residual stress (a) $S_{11}$ and (b) $S_{22}$ with depth from free surface at the different magnitude of the bed preheat temperature [12] ................................................................. 19

Figure 2.7. Deflection and residual Von Mises (S, Mises) stress (Pa) distribution in mesoscale hatch model ........................................................................................................................................... 21

Figure 4.1. Schematic representation of the mesoscale model and electron beam with respect to the part scale component .............................................................................................................. 25
Figure 4.2. Schematic representation of the model domain assuming two-fold symmetry about the beam path ................................................................. 25
Figure 4.3. Mesh topography of the domain ............................................................... 26
Figure 4.4. Temperature-dependent a) thermal conductivity (k), and b) specific heat capacity (C_p) of Ti-6Al-4V alloy [12], [31], [50] .................................................................................................................. 29
Figure 4.5. Mechanical properties of Ti-6Al-4V alloy (a) elastic modulus [6], [21], (b) yield strength [51] .................................................................................................................. 31
Figure 4.6. Mechanical properties of Ti6Al4V alloy (a) differential thermal expansion coefficient, (b) Poisson’s ratio [6] .................................................................................................................. 33
Figure 4.7. Thermal boundary conditions in the model .................................................. 35
Figure 4.8. Mechanical boundary conditions imposed on the domain ............................ 37
Figure 5.1. Nodal temperature distribution at 0.008 s when the beam is halfway in the domain. 39
Figure 5.2. (a) Melt pool length and depth, (b) Melt pool half-width .................................. 40
Figure 5.3. Comparison of (a) length, (b) width, (c) depth of melt pool of the base case with [44] .................................................................................................................. 40
Figure 5.4. The nodal temperature contour plots at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer .................................................................................................................. 43
Figure 5.5. The normal stress in the X direction (S11) contour plot at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer .................................................................................................................. 44
Figure 5.6. The X-component of plastic strain (PE11) profiles at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer ................................................................. 46

Figure 5.7. The distribution of state variable in the domain at the end of processing the fourth layer .......................................................................................................................... 47

Figure 5.8. The contour plot of normal stress in the X-direction (S11) in MPa at 0.008 s highlighting the location where quantitative data has been extracted from the model ............... 48

Figure 5.9. Variation of stress (S11) and temperature in (a) Element A and (b) Element B (see locations in Figure 5.8) with time during electron beam melting of the first powder layer ....... 49

Figure 5.10. Variation of plastic strain (PE11) and temperature in (a) Element A and (b) Element B (see locations in Figure 5.8) with time during melting of the first powder layer .......... 51

Figure 5.11. Plastic strain (PE11) profile on the YZ surface after processing and cooling the 1st, 2nd, 3rd, and 4th layers to the substrate temperature (682 °C) ....................................................... 53

Figure 5.12. Stress (S11) profile (MPa) on cooling the 1st, 2nd, 3rd, and 4th layers to the substrate temperature on the YZ surface ........................................................................ 54

Figure 5.13. (a) The vertical profile of plastic strain (PE11) and (b) the vertical profile of stress (S11) in the domain after the cooling of four powder layers to substrate temperature .......... 55

Figure 5.14. Effect of substrate temperature on the vertical profile of (a) plastic strain (PE11) and (b) stress (S11) after processing and cooling the fourth layer. Note that the data has been extracted from the centroid of each element .......................................................... 57

Figure 5.15. Comparison of the vertical profile of (a) plastic strain (PE11) and (b) longitudinal stress (S11) on cooling the four layers to the substrate temperature for different values of beam power ........................................................................................................ 58
Figure 5.16. Comparison of the vertical profile of (a) plastic strain (PE11) and (b) longitudinal stress (S11) on cooling the four layers to the substrate temperature for different values of beam speed. ................................................................. 60

Figure 5.17. Comparison of the plastic strain (PE11) model predictions (EB-PBF) with literature results [18], [27] ........................................................................................................ 62

Figure A.1. Contour plots (YZ surface) show the effect of substrate temperature on (a) longitudinal stress S11 (MPa), (b) plastic strain (PE11) when the four added layers are cooled down to the substrate temperature. .................................................................................. 74

Figure A.2. Melt pool contours for (a) 740 W (b) 840 W (c) 940 W beam power .......... 75

Figure A.3. Comparison of melt pool dimensions (a) Length, (b) Width, (c) Depth for different beam powers ........................................................................................................................................... 75

Figure A.4. Contour plots (YZ surface) showing the effect of beam power on (a) longitudinal stress S11 (MPa), (b) plastic strain (PE11) when the four added layers are cooled down to the substrate temperature. ........................................................................................................................................... 76

Figure A.5. Melt pool contours highlighting the effect of the beam speed: (a) 300 mm s⁻¹, (b) 500 mm s⁻¹, (c) 700 mm s⁻¹ ............................................................................................................................................... 77

Figure A.6. Comparison of the dimensions of melt pool of the model prediction with literature results ........................................................................................................................................... 77

Figure A.7. Contour plots (YZ surface) showing the effect of beam speed on (a) S11 (MPa), (b) PE11 when the four added layers are cooled down to the substrate temperature. ......................... 78
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Units</th>
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<tbody>
<tr>
<td>$A$</td>
<td>powder absorptivity</td>
<td></td>
</tr>
<tr>
<td>$A_S$</td>
<td>surface area</td>
<td>mm$^2$</td>
</tr>
<tr>
<td>$a$, $b$, $c$</td>
<td>semi-axes of the ellipsoid in x, y, and z directions</td>
<td>mm</td>
</tr>
<tr>
<td>$C_P$</td>
<td>specific heat capacity of the material</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$F_i$</td>
<td>internal forces per unit volume in the i direction</td>
<td>N</td>
</tr>
<tr>
<td>$f_L$</td>
<td>liquid fraction</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>heat transfer coefficient</td>
<td>W mm$^{-2}$ K$^{-1}$</td>
</tr>
<tr>
<td>$K_{ij}$</td>
<td>submatrix of the fully coupled Jacobian matrix</td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>temperature-dependent thermal conductivity</td>
<td>W mm$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$k_{pow}$</td>
<td>powder thermal conductivity</td>
<td>W mm$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$k_{bulk}$</td>
<td>bulk thermal conductivity</td>
<td>W mm$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$P$</td>
<td>power of the energy source</td>
<td>W</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat flux</td>
<td>W mm$^{-2}$</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>heat energy produced per unit volume</td>
<td>W mm$^{-3}$</td>
</tr>
<tr>
<td>$q_{con}$</td>
<td>conductive heat transfer</td>
<td>W mm$^{-2}$</td>
</tr>
<tr>
<td>$q_{rad}$</td>
<td>heat loss due to radiation</td>
<td>W mm$^{-2}$</td>
</tr>
<tr>
<td>$r$</td>
<td>radial distance</td>
<td>mm</td>
</tr>
<tr>
<td>$R_u$</td>
<td>Mechanical residual vector</td>
<td></td>
</tr>
<tr>
<td>$R_\theta$</td>
<td>thermal residual vector</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>absolute temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_0$</td>
<td>mechanical coherency temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_r$</td>
<td>room temperature</td>
<td>K</td>
</tr>
<tr>
<td>$T_{ambient}$</td>
<td>ambient temperature</td>
<td>K</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>correction to the incremental displacement</td>
<td>mm</td>
</tr>
<tr>
<td>$v$</td>
<td>speed of the beam</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>total or secant thermal strain coefficient</td>
<td>K$^{-1}$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Parameter</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$\alpha'$</td>
<td>tangent to the thermal strain curve</td>
<td>K$^{-1}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Emissivity</td>
<td></td>
</tr>
<tr>
<td>$\epsilon'$</td>
<td>Inherent strain tensor</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{th}$</td>
<td>Thermal strain</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{pl}$</td>
<td>Plastic strain</td>
<td></td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>energy conversion efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_e$</td>
<td>electron beam efficiency</td>
<td></td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td>correction to the incremental temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of the material</td>
<td>kg mm$^{-3}$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stephan Boltzmann constant</td>
<td>W mm$^{-2}$ K$^{-4}$</td>
</tr>
<tr>
<td>$\sigma_{beam}$</td>
<td>beam sigma</td>
<td>mm</td>
</tr>
<tr>
<td>$\sigma_{comp}$</td>
<td>Compressive stress</td>
<td>MPa</td>
</tr>
<tr>
<td>$\sigma_{res}$</td>
<td>Residual stress</td>
<td>MPa</td>
</tr>
<tr>
<td>$\sigma_{tens}$</td>
<td>Tensile stress</td>
<td>MPa</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>Yield Stress</td>
<td>MPa</td>
</tr>
<tr>
<td>$\tau_{ij}$</td>
<td>shear stress in the j direction</td>
<td>MPa</td>
</tr>
<tr>
<td>$\phi$</td>
<td>volume fraction of porosity</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>maximum radius of the laser spot</td>
<td>mm</td>
</tr>
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Acknowledgments

I would like to express my deepest gratitude to my supervisors, Prof. Steve Cockcroft, Prof. Daan Maijer, and Dr. Farzaneh Farhang Mehr for their invaluable insight into developing the methodology presented in this thesis. Their unwavering support and patience during the duration of this project enabled me to produce quality work. I am grateful for their constructive criticism and practical suggestions during various group meetings and presentations over the course of the project.

Especially helpful to me during this time was my research colleague Pegah Pourabdollah who provided me with valuable suggestions about my modeling methodology and technical assistance. I very much appreciate my fellow students from the Advanced Materials Processing group for their suggestions, advice, and assistance.

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Finally, I would like to thank my parents and friends for their constant encouragement and profound belief in my abilities. I am indebted to my husband Sounik for his unconditional love and cooperation. My success would not have been possible without their support.
Chapter 1: Introduction

Additive manufacturing (AM) is a layer-by-layer, incremental manufacturing technique, where filament / wire, sheet, or powder are consolidated into components by selectively melting/sintering the feed materials [1]. Starting from a digital geometric model, the part is divided or “sliced” into layers, and then the AM machine deposits or melts the material in layers to form a three-dimensional component. AM offers several advantages over subtractive manufacturing methodologies (like conventional machining) such as the ability to produce parts directly from a 3D Computer-Aided Design (CAD) file, reduced material waste during the production of parts, and in some cases, the ability to produce part geometries that cannot be manufactured by machining [1], [2].

In recent years, AM has garnered significant interest from industry and academia as a fabrication method for complex three-dimensional geometric shapes. According to the Wohler Report 2021 [3], there has been an exponential increase worldwide in the amount spent on parts produced via AM from 1994 to 2020 as presented in Figure 1.1.

Titanium, stainless steel, aluminium, and nickel alloys are some of the common metallic materials that are printed using different types of AM processes. Table 1.1 summarizes the metals and alloys commonly used in AM and the industrial sectors where they are employed. Figure 1.2 shows examples of a 3D printed turbine blade [4] and a tailored medical component produced from titanium [1].

Figure 1.1. Annual expenditures on part production by AM worldwide in millions of dollars ($M) [3]

<table>
<thead>
<tr>
<th>Year</th>
<th>Millions of dollars ($M)</th>
</tr>
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<tbody>
<tr>
<td>94</td>
<td>$0</td>
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<td>18</td>
<td>$0</td>
</tr>
<tr>
<td>20</td>
<td>$5,000</td>
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Table 1.1. Common metals and alloys used in additive manufacturing applications [4], [5]

<table>
<thead>
<tr>
<th>Alloys→Applications↓</th>
<th>Aluminum</th>
<th>Stainless steel</th>
<th>Titanium</th>
<th>Cobalt chrome</th>
<th>Nickel superalloys</th>
<th>Precious metals</th>
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<tr>
<td>Aerospace</td>
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<td>X</td>
<td>X</td>
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<tr>
<td>Medical</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Marine</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 1.2. (a) 3D printed turbine blades [4] and (b) Titanium skull implant [1]

1.1 Classification of the Metal Additive Manufacturing Processes

According to the ISO/ASTM 52900 standard of AM technologies [5], AM processes can be classified into seven categories based on their consolidation methodology: binder jetting, material extrusion, directed energy deposition (DED), material jetting, powder bed fusion (PBF), stereolithography and sheet lamination. In metal-based AM processes, high-energy heat sources such as a laser or an electron beam are used to locally melt feedstock materials into a dense metallic component. Where appropriate, the heat source and adhesion methodology are combined to define the process. Some of the common metal-based AM processes are:

- Laser Direct Energy Deposition (L-DED) - a laser heat source creates a melt pool and wire, or powder is fed into the melt pool as the laser scans the bed.
• Electron Beam-Ded (E-DED) – an electron beam heat source creates a melt pool and wire is fed into the melt pool.
• Preheating Laser Powder Bed Fusion (L-PBF) - a laser heat source is used to consolidate thin layers of powder.
• Electron Beam-PBF (EB-PBF) – an electron beam heat source is used to consolidate thin layers of powder.

As this thesis focuses on the EB-PBF process, the EB-PBF process is introduced in the next subsection.

1.2 Electron Beam Powder Bed Fusion (EB-PBF) Technology

The first commercial EB-PBF AM machine was developed by Arcam AB Corporation in Sweden in 1997 [6], [7]. Figure 1.3 shows a schematic view of an EB-PBF machine set-up. The feed powder and build stage are contained in a vacuum environment at a high vacuum (< $10^{-4}$ mbar). A thin layer of powder is “raked” across the build area at the start of processing each layer. Electromagnetic coils are used to focus and move the electron beam. When heating or melting, the electron beam is rastered across the surface of the powder. While processing each layer, there may be two or more heating steps. Initially, each new powder layer is pre-heated with a defocused beam to improve the electrical conductivity of the powder bed and prevent the build-up of electric charge, which can lead to “smoking” where the powder is ejected from areas in close proximity to the electron beam. Preheating can also result in reduced stress and distortion in built parts. A focused electron beam is then used to melt regions of the powder to form the cross-section of the part on the current layer [8],[9],[10]. Finally, in some instances, a post-heating step may occur with a defocused beam prior to lowering the build table and adding the next layer of powder.
1.3 Advantages and drawbacks of the EB-PBF process

The EB-PBF process provides significant advantages over other AM processes in manufacturing geometrically complex components with high dimensional accuracy without tooling. It has lower contamination-related defects due to building the components in a high vacuum environment [7]. It also has faster build rates, higher energy density, and improved energy efficiency compared to laser-based AM processes [11].

However, the EB-PBF process faces significant challenges. One of the major disadvantages of AM processes is the presence of residual stress within the fabricated parts. In both PBF technologies (i.e., EB-PBF and L-PBF), repeated heating and cooling of the powder layer generates large thermal gradients and has the potential to cause plastic deformation [12]. Residual stresses may result in part distortion and a loss of dimensional accuracy in the final component. Lastly, another challenge common to all of the metal AM processes utilizing powder is the high cost incurred in materials and equipment [13].
1.4 Defects in EB-PBF produced parts

There are a number of defects, such as porosity, residual stress, and geometric distortion, that can occur in parts produced via EB-PBF processes. Several studies have been published that focus on defect formation in additively manufactured parts. The defects observed in AM parts are linked to the specific AM technique employed to fabricate a part and will vary from one process to another. A classification of the significant defects that are typically formed in most of the AM manufactured parts is shown in Figure 1.4.

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Flaws</th>
<th>Microstructure</th>
<th>Dimensional</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Spherical gas porosity</td>
<td>• Lack of fusion</td>
<td>• Banding</td>
<td>• Distortion</td>
</tr>
<tr>
<td>• Cluster porosity</td>
<td>• Inclusions</td>
<td>• Segregation</td>
<td>• Stair stepping</td>
</tr>
<tr>
<td>• Voids</td>
<td>• Contaminants</td>
<td></td>
<td>• Surface condition</td>
</tr>
</tbody>
</table>

Figure 1.4. Classification of AM defects

One of the most common and problematic defects in parts fabricated via PBF processes is porosity. Three primary mechanisms lead to the formation of porosity: (a) “keyholing”, (b) gas entrapment; and (c) inadequate melting. Keyholing refers to the localized vapourization of metal that can occur close to the heat source. This phenomenon occurs when excessive heat energy is applied and will be influenced by the base metal, alloying elements, and the combination of the total pressure in the chamber and equilibrium vapor pressure above the molten metal [6]. Gas entrapment pores occur when gases contained within the feedstock are trapped within the AM part [1]. The vacuum environment necessary for EB-PBF processes eliminates the gas between particles in the powder bed, but it is possible to have gas encapsulated within powder particles which can lead to entrapped gas pores [1],[14].

The application of a rapidly moving, high-intensity heat source, i.e., the Electron Beam (EB), or Laser (L) to melt the powder bed, leads to repeated, rapid heating and cooling cycles in the component. One consequence of this is the development of in-situ stresses and subsequent distortion, and dimensional inaccuracy [3, 4]. An additional source of large thermal stresses may be the thermal expansion mismatch between the starter plate and the component [1]. Excessive residual stress and/or distortion may result in degradation of the component performance. If present after processing, tensile residual stresses may leave a component susceptible to fatigue
failure by reducing the applied stress necessary for crack initiation and growth. [16]. High thermal stresses during processing can also cause cracking or delamination and combined with residual stress can hinder the service life of a component [15].

1.5 Motivation

In order to control residual stress and distortion, one must understand their evolution during AM processing. Experimental measurements of residual stress and deformation in EB-PBF can be expensive and time-consuming [17]. One possible recourse is the use of numerical models like finite element (FE) modelling to predict the thermomechanical behaviour of parts in the AM process. These models reveal the thermal and deformation history during processing from which the evolution of residual stress can be investigated. The development of a numerical thermo-mechanical model can facilitate the establishment of the relations between the process parameters and the temperature distribution, residual stress, and distortion.
Chapter 2: Literature Review

This chapter will review the recent studies on residual stress and distortion development during additive manufacturing (AM). Firstly, the origin of residual stress and distortion in PBF-based AM processes will be reviewed. Then, the experimental and modelling approaches used to study the development of residual stress in EB-PBF will be summarized. Due to the lack of sufficient literature on residual stress development in EB-PBF, previous work done on the residual stress evolution and modelling in laser-based PBF process (L-PBF) will also be examined. The literature reviewed will then be used to identify the current challenges and research gaps in modelling residual stress and distortion in AM parts.

2.1 Distortion and residual stress evolution in EB-PBF

As noted in Chapter 1, residual stress and distortion commonly occur in parts produced by PBF processes and if excessive, may be classified as a defect [15] [18]. Residual stress originates from the combined effects of differential thermal expansion/contraction and constraint from the plate that the part is built on and from previously processed layers. One of the factors that affect the evolution of the stress distribution during processing is the temperature gradient caused by the moving heat source. The rapid transients and large thermal gradients combine with temperature-dependent constitutive and thermal expansion/contraction behaviour to result in the development of thermal stresses [7],[15].

The effect of the temperature history on the stress in a part has been captured in the temperature gradient model (TGM) proposed by Mercelis et al. [18]. In this model, the local thermal expansion, caused by the rapid heating of the feedstock material, is constrained by cold surrounding material and results in compressive stresses in the hot zone, shown schematically in Figure 2.1. During cooling, when the heat source is deactivated or has moved away, the molten material solidifies and cools resulting in contraction. The solid material surrounding the molten area restrains the solidification shrinkage and thermal contraction occurring during cooling. After solidification and subsequent cooling, the previously molten material is left in a state of tensile residual stress that is balanced by a surrounding compressive region. Plastic strains and residual stresses will result in distortion in the part.
Distortion can also be influenced by solid-state phase transformations that occur as the part cools from the solidus to room temperature [20]. Examples of these phase transformations include the austenite to ferrite transformation in steel and the \( \beta \) to \( \alpha \) transformation in Ti-6Al-4V alloy. As the material undergoes a phase transformation, the material may exhibit contraction/expansion, or in the presence of stress, "transformation plasticity" may occur, and will affect the magnitude of the final residual stress in the component [20]. This form of residual stress, caused by phase transformations, was studied by Bailey et al. [21] for AISI H13 tool steel components produced via L-DED.

Another factor contributing to the final residual stress distribution and distortion in a part is stress relaxation that can occur due to the thermal effects of layer-by-layer mass deposition and heating. As materials are heated above a specific temperature, annealing can occur, relieving some of the existing stresses [22].

### 2.2 Experimental Characterization of Residual Stress and Distortion in the PBF process

There have been several experimental studies on the residual stress and distortion in PBF processes. While investigating the effects of residual stress on dimensional accuracy, Prabhakar et al. [23] observed warping in Inconel 718 components fabricated by an EB-PBF process. The built parts were fabricated on a stainless-steel base plate using the electron beam melting (EBM) process in an Arcam EBM system. It was observed that the top surface of the base plate bulged upward.
during the build process thereby deforming the built parts. The bulge in the base plate reduced with an increasing number of layers in the build, which showed that the layers built later were less deformed than the initial layers of the build. After cooling down, there was a permanent upward warp in the base plate. The bottom layers in the built parts were distorted more than the upper layers. Predictions from a thermomechanical model of the build showed qualitative agreement with the deformations observed in the base plate and the built parts (see Figure 2.2). However, the effect of process variables on distortion was not studied in this research.

Strantza et al. [24] studied the residual stress evolution in a Ti-6Al-4V component produced by the L-PBF process. They used X-ray diffraction to evaluate the three-dimensional residual strain and stress state in the built part. A laser power of 100 W, a scan speed of 600 mm/s, and a beam diameter of 54 µm were used in the L-PBF process, along with a layer thickness of 30 µm and hatch spacing of 105 µm. It was observed that the x and y components of stress were mainly tensile for the chosen cross-section of the measurement. The z component of stress exhibited high tensile values at the edges of the part but was compressive across the interior. The maximum deviation of the measured values from a computational model was found to be 20%.

Figure 2.2. (a)-(b) Experimental results of AM part showing warping; and (c)-(d) Corresponding modeling result [23]
Liu et al. [25] studied the effect of heat input on the formation of residual stress in 316L stainless steel bars produced via the L-PBF process. The distribution of residual stress in the final part was measured experimentally by X-ray diffraction. The energy input was controlled by changing the beam speed, e.g. slow scanning speeds associated with high heat inputs. The residual stress distribution was measured along a scanning line that traversed the part. It was found that the qualitative distribution of residual stress was not affected (e.g. tensile/compressive stress states occurred in similar locations after each build), but quantitatively, the peak of the residual stress increased with the energy input. For higher heat input (200 W and 200 mm s\(^{-1}\)), residual stress of ~210 MPa was observed, while for the lowest heat input (200 W and 800 mm s\(^{-1}\)), the residual stress was ~30 MPa.

Various methods have been proposed by researchers to reduce residual stress in laser and electron beam PBF processes[26]–[28] such as heat treatment or Hot Isostatic Pressing (HIP), controlling the beam process parameters (speed, preheating temperature, beam power) and the use of support structures. Numerical modeling of the thermomechanical behaviour of the EB-PBF process can also give an estimation of the magnitude, state, and distribution of residual stress. An overview of the modeling methodology for EB-PBF processes and the work done by previous investigators on residual stress modeling and experimental validation are discussed in the following section.

2.3 Modeling Methodology of residual stress in AM

Experimental measurements of residual stress and deformation in AM parts are difficult and expensive to perform. One possible way of mitigating these factors is the use of numerical models to predict thermomechanical behaviour during AM. These numerical models consider the temperature-dependent material properties, phase transformation from powder to liquid metal, as well as the transformation from liquid to solid metal. However, even for small-scale components, computational modelling can require significant computational resources and time. For example, residual stresses and distortion calculations for an actual process time of 2 seconds can take up to 460 hours [1]. The required calculation time may vary depending on the efficiency and capability of the computing facility. Various investigators have reported on their efforts to simulate the heat transfer and mechanical deformation during metal printing to predict the residual stress distribution and distortion. In this section, a summary of such model development is provided.
2.3.1 Heat Transport Phenomena in EB-PBF

The heat transport, within the melt-pool and the surrounding material, during EB-based metal powder bed fusion is affected by a number of complex phenomena. The schematic shown in Figure 2.3 illustrates the heat transfer and some of the melt pool dynamics that occur during the process including the following:

1. Electron beam heat input
2. Radiation heat loss
3. Diffusive heat transport
4. Advective heat transport in the melt pool is caused by:
   a. Marangoni forces due to thermal gradients (and compositional gradients if present)
   b. Buoyancy forces
5. Heat loss due to evaporation (e.g., preferential evaporation of Al when melting Ti64 alloy)

When the electron beam heats the powder layer, a large fraction of the beam’s kinetic energy is transformed into thermal energy, which heats the powder in close proximity to the electron beam. The transport of heat in the solid materials depends on the thermal diffusivity and contact conditions in the powder, and once a molten pool forms, it is dependent on a combination of advection and diffusion transport processes. Marangoni force is one of the dominant flow drivers in the melt pool that originates from gradients in surface tension. The gradients in surface tension can arise due to gradients in temperature and/or composition. A composition gradient can form due to preferential evaporation of the high vapour pressure species within the alloy. Depending on the alloy system, the gradient in surface tension can induce fluid motion away from or toward the beam.
Figure 2.3. Schematic highlighting the physical phenomena occurring as an electron beam melts a layer of metal powder

Different techniques have been used to model the heat transport in AM processes such as finite element analysis (FEA) and computational fluid dynamics (CFD) analysis. Commercial FEA packages, such as ABAQUS\(^1\) and ANSYS\(^2\) have been utilized to solve the energy (heat) conservation equations to estimate the 3D transient or steady-state temperature distribution. The predicted temperature distribution can provide valuable insight into the melt pool dimensions. For a three-dimensional domain, the transient temperature response can be calculated by solving the energy conservation equation given below [29]:

\[
\rho(T)C_p(T) \frac{dT}{dt} = \frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + \dot{Q}
\]

Equation 2.1

where \(\rho(T)\) (kg m\(^{-3}\)) is the density of the material which is dependent on the absolute temperature \(T(K)\), \(t\) (s) is the time, \(C_p(T)\) (J K\(^{-1}\) kg\(^{-1}\)) is the specific heat capacity of the material, \(k(T)\) (W m\(^{-1}\) K\(^{-1}\)) is the temperature-dependent thermal conductivity, \(\dot{Q}\) (J m\(^{-3}\) s\(^{-1}\)) is a volumetric source term to account for the latent heat of phase transformations, and \(x\), \(y\), and \(z\) (m) are the coordinates.

Shen \textit{et al.}[14] simulated EB-PBF of a Ti6Al4V alloy by conducting a transient heat transfer analysis incorporating a moving Gaussian volumetric heat source in the ABAQUS FEA software. The effect of beam spot size and powder porosity on the melt pool size was studied. Consistent with the vacuum environment, convection between the powder layer and the surrounding environment was omitted and heat loss via radiation was included. The powder layer

\(^1\) ABAQUS is a trademark of Dassault Systemes
\(^2\) ANSYS is a trademark of ANSYS Inc.
and substrate were initialized with a uniform temperature distribution ($T_{\text{preheat}}$). The temperature of the bottom surface of the solid substrate was held at a constant temperature of $T_{\text{preheat}}$ as a thermal boundary condition. The emissivity and thermal conductivity of the powder were assumed to be functions of powder porosity based on Sih et al.’s work [30]. The process parameters, such as the scan speed, beam current, etc., were determined for EB-PBF from the literature. Then, the powder layer porosity was varied from solid (0) to 0.6 to investigate the effect of powder porosity on thermal responses, i.e., temperature field, temperature history, as well as heating/cooling rates. The depth of the melt pool and maximum temperature were predicted to decrease with increasing beam spot size, due to decreasing energy density. In addition, a higher maximum temperature occurred at a higher porosity. The melt pool became deeper and shorter with the increase of porosity. However, the width of the molten pool did not change with porosity due to greater thermal resistance on both sides of the scan path. The model was validated by comparison to results reported in the literature and with measured data from the Laser Engineered Net Shaping (LENS) process, which has a similar configuration to the EB-PBF process.

Several researchers have accounted for the transformation of material properties with the change of state, i.e., powder material to liquid metal and then to solid metal. Galati et al. [9] utilized user-defined subroutines in ABAQUS to simulate EB-PBF of Ti6Al4V alloy and included the temperature dependence of material properties. UMATHT and USDFLD subroutines were used to solve the energy conservation equation using a material index based on temperature history (e.g., powder or bulk) to update material properties. Thermal boundary conditions describing the EB heating and radiative heat losses were incorporated into the model using the DFLUX and FILM subroutines. The model melt pool dimensions were validated against experimental results and the maximum deviation was found to be 25%.

Jamshidinia et al. [31] developed a three-dimensional thermal-fluid flow model of the EB-PBF processing of Ti6Al4V alloy using the ANSYS FLUENT software. The temperature dependence of material thermal properties was included in the model through a user-defined function. The predicted melt pool depth and width were validated against experimental measurements on parts built using an ARCAM EB-PBF machine and the maximum deviation was found to be 3.5%.
2.3.2 Descriptions of PBF Heat Sources

One of the key features of a PBF process model is the approach used to incorporate the heat source. Common techniques for describing laser or electron beam heating assume that the heat energy being applied has a Gaussian distribution. The distribution of heat energy, $q$, is calculated using either a heat flux on the top surface or a volumetric heat input in a small volume depending on the penetration depth of the heat flux. Both area and volumetric heat equations have been used in the literature to simulate the heat source. Table 2.1. Different heat source models used in the literature [29] summarizes the conventional heat source models used by previous investigators. In the table, $Q$ (W) is the heat source power, $a$, $b$, and $c$ (m) are the dimensions of an ellipsoid in x, y, and z directions (m), $A$ is powder absorptivity, $d$ (m) is the penetration depth of the heat source, $\omega$ (m) is the standard deviation of the beam. 

Table 2.1. Different heat source models used in the literature [29]

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Equation</th>
<th>References</th>
<th>Temperature distribution obtained from Gaussian heat source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian Heat source</td>
<td>$q(x, y)(W \ m^{-2}) = \frac{2Q}{\pi \omega^2} \exp\left(\frac{-2[x^2 + y^2]}{\omega^2}\right)$</td>
<td>[32]</td>
<td></td>
</tr>
<tr>
<td>Moving heat source</td>
<td>$q(x, y, z)(W \ m^{-3}) = \frac{6\sqrt{3Q}}{abcp\sqrt{\pi}} \exp\left(-\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c^2}\right)$</td>
<td>[22]</td>
<td></td>
</tr>
<tr>
<td>Volume related</td>
<td>$q(x, y)(W \ m^{-3}) = \frac{A}{d} \exp\left(-\frac{z}{d}\right) \frac{2Q}{\pi \omega^2} \exp\left(-\frac{2x^2 + 2y^2}{\omega^2}\right)$</td>
<td>[33]</td>
<td></td>
</tr>
</tbody>
</table>

2.3.3 Latest Research in Modeling and Validation of Residual Stress

Several researchers have studied the evolution of residual stress in AM components by developing finite element (FE) based mathematical models. In these models, the material transformations from metal powder to liquid metal and from liquid metal to solid and the effects of these transformations on material properties have been accounted for using a variety of approaches. The transport processes involved occur over a broad range of length scales; as a result, these models are complex, and the execution times are typically very long.

Due to the limited availability of literature related to the residual stress modeling of components fabricated with the EB-PBF process, studies focused on L-PBF will also be considered in this section. The range of process parameters common in EB-PBF and L-PBF are summarized in Table 2.2. One of the key differences between laser and EB-based PBF is that only 10-20% of
the beam power in the L-PBF process reaches the part. In contrast, in the EB-PBF process, the overall energy efficiency is around 0.85-0.9. Also, the beam speed in the EB-PBF process can be much higher (e.g., 4 vs. 1.2 m s\(^{-1}\)) than in the L-PBF process. The combination of these capabilities facilitates different processing regimes in E-PBF such as the ability to maintain multiple simultaneous melt pools [1].

Table 2.2. Comparison of the L-PBF and EB-PBF process parameters [1], [34]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>L-PBF</th>
<th>EB-PBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder size (µm)</td>
<td>10-60</td>
<td>50-150</td>
</tr>
<tr>
<td>Layer height (µm)</td>
<td>30-60</td>
<td>50-100</td>
</tr>
<tr>
<td>Preheating temperature (°C)</td>
<td>up to 500</td>
<td>650-1100</td>
</tr>
<tr>
<td>Preheat method</td>
<td>Heated base plate</td>
<td>Electron Beam</td>
</tr>
<tr>
<td>Speed of the beam (m s(^{-1}))</td>
<td>0.8 - 1.2</td>
<td>0.1 - 4</td>
</tr>
<tr>
<td>Beam power (W)</td>
<td>50 - 1000</td>
<td>50-1000</td>
</tr>
<tr>
<td>Beam Efficiency</td>
<td>0.1-0.2</td>
<td>0.85-0.9</td>
</tr>
<tr>
<td>Environment</td>
<td>Inert gas</td>
<td>Vacuum</td>
</tr>
</tbody>
</table>

In numerical models of thermal stress development in AM components, a thermal analysis step is used to calculate the temperature distribution during the build, and a mechanical analysis step is used to calculate the stress development and distortion due to the thermal loads. The analysis steps can be ‘weakly’ / sequentially coupled (e.g. thermal predictions are used as loads in the mechanical analysis) [35] or fully coupled (e.g. where stress/distortion can influence the thermal field and vice versa) [36]. Luo et al. [37] presented a typical workflow for a weakly coupled thermomechanical analysis of a part produced by a PBF process (see Figure 2.4). The sequentially coupled approach is often used due to the reduced computational times.
Prior to running a model, there is a pre-processing step to define the part geometry, the mesh, and the initial and boundary conditions. Following the pre-processing step, the thermomechanical simulation solves the following governing equations (sequentially or fully coupled) to predict the evolution of the temperature (refer to Equation 2.1) and the stress distribution based on the following equations [38]:

\[
\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = F_x \tag{Equation 2.2}
\]

\[
\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} = F_y \tag{Equation 2.3}
\]

\[
\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} = F_z \tag{Equation 2.4}
\]

In the above equations, \(x, y,\) and \(z\) (m) are the coordinates. \(\sigma_x, \sigma_y, \sigma_z\) (Pa) are the components of normal stress in the \(x, y,\) and \(z\) directions respectively. \(\tau_{ij}\) (Pa) denotes the shear stress in the \(j\) direction and \(F_i\) (N m\(^{-3}\)) are internal forces per unit volume in the \(i\) direction.
A detailed model that considers the effects of each aspect of the process on each layer of the part would include the deposition of material, the movement of the heat source for pre-heating, sintering, and/or post-heating, and interlayer processes, as well as the final cool down after the build is complete.

Numerous studies have considered the effect of PBF process parameters on the residual stress distribution in additively manufactured parts. These studies have shown that residual stress is dependent on the following parameters:

1. **Pre-heat temperature**
2. **Sintering Strategy**
3. **Heat input**
4. **Speed**

One important aspect of the prediction of the residual stress and deformation in the PBF process is the quantification of the in-elastic strain during the solidification of the melt pool. When the molten layer cools down; the substrate and the newly added layer are essentially isothermal. At this stage, the residual stress is driven by the magnitude of residual plastic strain in the component [19].

Mukherjee et al. [17] analyzed the residual stress and distortion forming in parts made from IN718 and Ti6AlV powders in the L-PBF process. They used a sequentially coupled model, combining the temperature history predicted by an in-house developed, heat transfer and fluid flow model and an ABAQUS-based FE model to simulate the deposition of ten powder layers. A Python script was developed to map the transient temperature fields from the heat transfer and fluid flow model to the mechanical model using the application programming interface (API) in ABAQUS. The boundary conditions for the mechanical analysis included constraints on the bottom surface of the substrate, i.e., the displacements of all nodes on the bottom surface were assigned a value of zero in the x, y, and z directions. To examine the effect of heat input on the distortion and thermal strain, they proposed a strain parameter ($\varepsilon^*$) as an indicator of the susceptibility to distortion. The model was validated against experimental results reported by Shah *et al.* [39]. It was observed that by doubling the heat input from 12 J/mm to 24 J/mm, the distortion increased by $\sim250\%$, and the maximum longitudinal residual stresses were reduced by 20%. However, the authors did not comment on the effect of the process parameters on the inelastic deformation in this work.
Parry et al. [40] studied the effect of scanning strategy on the residual stress and distortion in the L-PBF process for Ti6Al4V alloy. Two types of scanning strategies, shown in Figure 2.5, were evaluated. A coupled thermomechanical FE model of the process was produced using the MSC Marc software [41]. The outer contour was scanned first, followed by the hatch scan. The results demonstrated reduced levels of stress and equivalent plastic strain at the end of scan paths using the alternate scan strategy due to the reduced temperature gradients at the end of each vector. A study was conducted to validate the simulated melted track widths with experimental samples processed on a Realizer SLM 50 for a single layer using the same parameters as the simulation. A maximum deviation of 14% was observed. The effect of the beam scanning strategy on the X, Y, and Z components of plastic strain was not covered in this work.

![Figure 2.5. Laser scan strategies used in L-PBF process: a) unidirectional and b) alternating [40]](image)

Vastola et al. [12] studied the process parameters affecting the stress development during EB-PBF processing of Ti6Al4V alloy with a coupled thermomechanical FE model. Each simulation was designed such that a single scan was made and then the beam was turned off to allow cooling of the material to the powder pre-heating temperature. They found that a significant reduction in the stress distribution occurring during processing could be achieved by preheating the powder bed. As shown in Figure 2.6, each increase of 50 °C in preheat temperature resulted in a ~20% reduction of the stress at the surface of the part. This effect arises from the fact that the thermal gradients are lower during melt processing when the powder-bed temperature is higher. A region of high stress was found surrounding the original scan track, both in-depth and width. This region, defined as the heat-affected zone (HAZ), was found to have a depth and width of approximately 200 µm. They also predicted that a small beam size was found to generate larger residual stresses within a smaller heat-affected zone (HAZ), and larger beam sizes had a larger HAZ with a more uniform stress distribution. When the beam power was increased by 20%, the
HAZ was seen to increase by 15% which also led to an increase in the magnitude of stresses generated. The scanning speed was seen to affect the depth of the HAZ, where lower scan speeds had a deeper HAZ. But the highest values of stress were not affected by the scan speed. Overall, this was consistent with the explanation that a lower scan speed allowed more time for heat conduction away from the melt pool and into the bulk metal. As a result, thermal gradients, similar in magnitude, occurred at a greater depth compared to higher scan speed. Their numerical model predicted the dependence of residual stress evolution on the process parameters. However, the results reported did not quantify the plastic strain generation during the successive layer deposition in the EB-PBF process.

Figure 2.6. Variation of the residual stress (a) $S_{11}$ and (b) $S_{22}$ with depth from free surface at the different magnitude of the bed preheat temperature [12]

Several modeling methodologies have garnered attention from researchers due to their potential to reduce computational time while providing an acceptable level of accuracy for the evaluation of residual stress in the PBF process. The most common of these approaches are:

1. **Superlayer method**
2. **Inherent strain method (ISM)**

Many researchers have used the “superlayer” approach for thermomechanical modeling of PBF processes. In this methodology, the geometry is divided into large layers with heights on the order of 10 to 20 printed layers, known as superlayers [42], [43]. Each superlayer is activated at an initial temperature selected in conjunction with the boundary condition representing thermal processing. In some cases, the superlayers are activated at the liquidus temperature of the material and allowed to cool for a time equivalent to the time required to process the material in the actual
process. In other cases, the material is added and uniform heat flux is applied over the entire superlayer before letting it cool down. This later method was used by Papadakis et al. [43] to predict the residual stress and distortion evolution for a double cantilever geometry produced with the L-PBF process. The model was created in the ANSYS commercial software package. The residual stress and distortion of the model were validated against experimental results and the maximum deviation was found to be 25%. This approach reduces the number of layer additions and does not track the location of the heat source on the surface of each layer. The benefits of this approach are a significant reduction in computational expense and time yet providing reliable structural results. The drawbacks of this method are that it does account for the temporal or spatial variation of heat input that may result from different scan strategies and it does not describe the local temperature gradients/strain history occurring in each layer of the build. The temperature history of each superlayer represents the average thermal response of the build layers and as such, does not capture the partial remelting of previous layers that can occur in PBF processes.

Zhang et al. [28] used the Inherent Strain Method (ISM) to predict the residual stress distribution in a part produced by the L-PBF process. In this approach, the macroscale mechanical response of the material is simulated by imposing a residual plastic strain (Inherent Strain) tensor in sintered regions in an FE-based model. Their model employing the ISM method was combined with topology optimization to improve L-PBF support structures. The inherent strain tensor (ε’) is defined as: {εx’, εy’, εz’, εxy’, εyz’, εzx’}. The shear strain components were set to zero as discussed by Siewert et al. [44]. In the research conducted by Zhang et al. [28], the magnitude of εx’ and εy’ were defined as -0.002 and -0.001 based on results from a mesoscale thermo-elastoplastic model. The simulation results were validated against measurements performed on parts fabricated on a Renishaw AM 250 SLM System. The distortion predicted using the ISM showed good agreement (average error of 6%) between the experimental and simulated results. However, the dependence of the inherent strain magnitude on process parameters like beam speed, power, and substrate temperature was not explored in this work.

Some researchers have adapted the inherent strain method in multiscale modelling of PBF processes. Li et al. [45] developed a multiscale modeling approach for fast prediction of residual stress in the L-PBF process involving a single layer of powder and having three stages of modeling:

1. Microscale scan model: A microscale model was developed to simulate the processing of a single track on the surface of a powder bed. This model uses a surface-based Gaussian
heat source. Once a stable melt pool was achieved, the temperatures field was extracted and converted into an equivalent heat input.

Figure 2.7. Deflection and residual Von Mises (S, Mises) stress (Pa) distribution in the mesoscale hatch model

2. Mesoscale layer hatch model: The equivalent heat source was then applied to a meso-scale layer model and a coupled thermal-mechanical analysis was then performed on a small domain with a fixed hatch pattern. The meso-scale residual stress distribution upon cooling to room temperature was extracted for use in the macro-scale part level predictions.

3. Macroscale part mechanical model: The mesoscale residual stress field was mapped to a macroscale part model to predict part distortion and the residual stress distribution. The macro-scale model is a mechanical simulation and does not consider the thermal aspects of the build.

Li et al.’s model was verified by validating the predicted distortions against experimental data. This approach was used to predict the mesoscale residual stress field as displayed in Figure 2.7. The meso-scale results show expansion of the hot layer was constrained by the surrounding cooler material during laser scanning. This causes compressive stresses on the top surface. Plastic deformation may occur when the yield stress of the material is reached. On cooling down to room temperature, contraction of the top layer is restricted by the surrounding material, leading to tensile residual stress development on the top surface. The authors did not report any results on the effect of processing conditions on the plastic strain distribution during the layer deposition in the L-PBF process. Moreover, the model comprises a single layer of powder addition, therefore the complexities of stress and strain evolution during the layer-by-layer addition of powder are not captured in this work.
2.4 Summary

In this chapter, the published studies on simulation of the distortion and residual stress of the PBF process were analyzed and reviewed. Numerical modeling can serve as an important tool to understand the effects of process parameters on the evolution of strains and residual stresses. The computational models described in the literature review were limited to the thermal and mechanical models that have been developed to study the residual stress evolution in PBF processes (mainly laser-based).

Researchers such as Zhang et al. [28] used the Inherent Strain Method (ISM) in which the macroscale mechanical response of the material was simulated by activating a residual plastic strain (Inherent Strain) tensor for the individual hatching regions in the FE-based model for L-PBF process. However, the development of thermal stresses and inelastic strains during the solidification of the melt pool for EB-PBF is complex and needs further work. Moreover, there is limited literature available on the build-up of residual stress and strain during the addition of several layers in the EB-PBF method. An opportunity exists to examine the formation of inelastic strain in close proximity to the melt pool as a function of the processing parameters by developing the micron / mesoscale thermomechanical model of the EB-PBF process involving multiple layers.
Chapter 3: Scope and Objective of the Research

The literature review highlighted that mathematical modeling has been used to study the generation of the residual stress and strain in parts fabricated with additive manufacturing processes. Many researchers have investigated the modeling and simulation of PBF processes; however, there are still critical challenges that must be addressed. Based on this, the main objective of this thesis is to study the accumulation of inelastic strain and residual stress in the proximity of the melt pool in EB-PBF.

To support this objective, the following tasks have been undertaken in this manuscript-based thesis:

1. Develop a mathematical thermomechanical model of the EB-PBF process of Ti6Al4V alloy at the micron / mesoscale level. The domain of the model will include multiple powder layers deposited on previously consolidated material. This model will help in calculating the processing stress and strain accumulated around the melt pool.

2. Incorporate the effects of the material's state transformation, i.e., powder to bulk, on the generation of the stress and strain. In addition, the model must address the constitutive behaviour and thermo-physical properties of the material at elevated temperatures where experimental data is unavailable in the literature.

3. Use the model to investigate the effects of various process parameters, such as scanning speed, beam power, and substrate temperature, on the evolution of stresses and strains in proximity to the melt pool – i.e., at the mesoscale.

In the present study, the thermal response of the proposed model of EB-PBF of Ti-6Al-4V alloy was validated against the existing experimental studies of the same additive technology and material conducted by Jamshidinia et al. [31]. The mechanical response will then be studied under nominal processing conditions using the model. A sensitivity analysis will then be performed by varying the process parameters like beam power and scan speed to study their effect on the inelastic strain and stress development.
Chapter 4: Three-Dimensional Model Development

This chapter will describe the detailed methodology of the development of a three-dimensional model of the EB-PBF process of Ti-6Al-4V alloy. The thermal-stress finite element (FE) model was made using the commercial FE software, ABAQUS version 2017.

4.1 Modeling Methodology

A 3D thermo-mechanical model of a meso-scale sub-domain taken from a larger part made from Ti-6Al-4V powder and processed by EB-PBF was developed for this study. The model was formulated in ABAQUS because of the ability to develop user-defined subroutines that describe the complex thermo-physical and thermo-mechanical material behaviour. This flexibility was used in the current work to describe the varying state of the material as it transitions from powder to liquid and then from liquid to bulk solid. The details of the model development process are presented in the following sections.

4.1.1 Governing Equations

ABAQUS can solve non-linear problems efficiently and offers the advantage to incorporate additional functionality through user-defined subroutines. This flexibility was used in this model to describe the EB energy source, the state of the material, and to calculate the thermal strain.

ABAQUS solves a fully coupled thermal displacement problem using the following equation:

\[
\begin{bmatrix}
K_{uu} & K_{u\theta} \\
K_{\theta u} & K_{\theta \theta}
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta \theta
\end{bmatrix} =
\begin{bmatrix}
R_u \\
R_\theta
\end{bmatrix}
\]

Equation 4.1

where \( K_{ij} \) is the submatrix of the fully coupled Jacobian matrix, \( \Delta u \) and \( \Delta \theta \) are the corrections to the incremental displacement and temperature respectively, and \( R_u \) and \( R_\theta \) are the mechanical and thermal residual vectors, respectively [38].

4.1.2 Computational Domain

The geometry of the 3D mesoscale model was created in ABAQUS CAE (see Figure 4.1 and Figure 4.2). The mesoscale domain's length, width, and height are 6 mm, 0.75 mm, and 1.2 mm, respectively. This meso-scale domain represents a sub-section from a larger component (refer to Figure 4.1). To reduce the computational size of the problem, the domain was assumed to be symmetric about the beam path (XY plane), as shown in Figure 4.1. The length in the X direction (direction of the beam path) was selected to eliminate the effects of the ends of the domain. In the
Y direction, the domain is sized to include four powder layers (each 0.1 mm height) and eight layers of the previously consolidated material or substrate (total 0.8 mm height). In the Z direction, the width of the domain is sufficient to allow the definition of an adiabatic boundary on the XY plane opposite to the symmetry boundary. Note: the speed of the beam is assumed to be sufficiently fast to limit the amount of heat transported to the XY plane opposite to the symmetry boundary, later in the thesis.

Figure 4.1. Schematic representation of the mesoscale model and electron beam with respect to the part scale component

Figure 4.2. Schematic representation of the model domain assuming two-fold symmetry about the beam path
The approximate domain size in ABAQUS must be between $10^{-3}$ to $10^{4}$ base units [46]. Since this is a mesoscale model, appropriate significant digits should be considered in the numerical calculations. Therefore, the units used for the analysis (e.g., the domain, material properties, etc.) were based on millimeters.

4.1.3 Mesh

The mesh topography in the domain is shown in Figure 4.3, and the mesh statistics are summarized in Table 4.1. An 8-node linear, reduced integration, element type was used to mesh the domain (C3D8RT). A constant mesh size (0.032 mm) was used in the X-direction and variable mesh sizes were defined in the Z and Y directions. In the Z-direction, the mesh changes from 0.032 mm to 0.18 mm with increasing distance from the beam path in both the substrate and the powder. In the powder, the mesh size is constant (0.032 mm) in the Y-direction, and in the substrate, it varies from 0.032 mm to 0.2 mm, with increasing distance from the interface between the 1st powder layer and the bottom of the domain.

![Figure 4.3. Mesh topography of the domain](image)

**Table 4.1. Mesh statistics**

<table>
<thead>
<tr>
<th>Domain</th>
<th>Element Type</th>
<th>Element shape</th>
<th>Number of Nodes</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>C3D8RT</td>
<td>Brick</td>
<td>15120</td>
<td>18036</td>
</tr>
<tr>
<td>Powder</td>
<td></td>
<td></td>
<td>20160</td>
<td>12024</td>
</tr>
</tbody>
</table>
4.1.4 User-Defined Subroutines

One of the primary reasons for choosing ABAQUS software is its capability to allow the incorporation of additional functionality through user-written subroutines. The subroutines used in the numerical model developed in this work are described in this section.

4.1.4.1 DFLUX subroutine

The ABAQUS subroutine DFLUX was used to define the distribution of heat input and motion of the electron beam. The expression used in the model is based on a normal distribution. It is applied to the surface and is translated from left to right, as described in section 4.1.6.1.

4.1.4.2 USDFLD subroutine

Material properties were defined as a function of state variables and temperature. The state variable was assigned to be zero for powder and one for bulk material using the USDFLD subroutine. The utility routine GETVRM was called to access the element temperature at every increment. The details of the assignment of the state variable are described in section 4.1.4. The state variable was stored for each material integration point, and used for further calculation of thermal strain.

4.1.4.3 UEXPAN subroutine

The UEXPAN subroutine can model the thermal expansion behaviour of materials in which the thermal strain is dependent on temperature and/or state variables in complex ways. The thermal strain increment was computed for both the metal and powder domain as a function of state variables and temperature.

4.1.5 Material Properties

An important aspect of the work is properly capturing the behaviour of Ti6Al4V in various forms encountered in the EB-PBF process – i.e., powder, liquid, and bulk solid. The approach used has been to define a state variable in ABAQUS that ranges from 0 to 1, representing the transition from powder to bulk. The variation in properties was implemented via the USDFLD user-defined subroutine. Previous work by Galati et al. [9] adopted a state variable approach to assign the properties of the powder, liquid, and bulk material to the material in a thermal finite element modelling of the EB-PBF process. This work extends their approach and links both the thermal and mechanical properties of the powder and the bulk material to a state variable. The USDFLD
subroutine was utilized for this. In the USDFLD subroutine, the utility routine GETVRM was called to access the elemental temperature at each increment. Below the solidus temperature, a state variable, defined at each integration point, was set to zero to represent Ti-6Al-4V powder. Between the solidus (1604 °C) and the liquidus (1660 °C) temperatures, the magnitude of the state variable was increased linearly from zero to one with temperature. Above the liquidus temperature, the state variable was set to one. Changes to the state variable cannot be reversed (i.e., the state variable cannot decrease) as the state of the powder has been permanently altered in terms of its volume fraction porosity. The state variable was stored for each integration point and used to assign material properties.

Another important aspect of the model formulation was to properly characterise the thermal expansion behaviour of Ti-6Al-4V in the various forms described above. The behaviour was captured using the UEXPAN subroutine. The details of this approach are discussed in the Thermal Expansion Coefficient section below.

Density - Density was defined as a constant value of $4.2 \times 10^6$ kg mm$^{-3}$ for the solid and $2.4 \times 10^6$ kg mm$^{-3}$ for the powder [12].

Thermal Conductivity - The thermal conductivity of powder is determined based on Equation 4.2.

$$k_{\text{pow}} = (1 - \phi) \ k_{\text{bulk}}$$

Equation 4.2

where $k_{\text{pow}}$ is the thermal conductivity of the powder (W mm$^{-1}$ K$^{-1}$), $\phi$ is the volume fraction of porosity (assumed to be 0.46 [47]), and $k_{\text{bulk}}$ is the temperature-dependent thermal conductivity of bulk Ti-6Al-4V.

The effective thermal conductivity of the powder ($k_{\text{pow, effective}}$) as it transitions to the bulk form is defined in terms of the field variable, as shown in Equation 4.3.

$$k_{\text{pow, effective}} = U_{\text{state}} \times k_{\text{bulk}} + (1 - U_{\text{state}}) \times k_{\text{pow}}$$

Equation 4.3

where $U_{\text{state}}$ is the magnitude of the state variable describing the state of the material, which varies between 0 for powder and 1 for bulk. The resulting relationships between thermal conductivity, material form, and temperature are shown in Figure 4.4 (a).

To account for the effect of advective heat transport, due to significant fluid flow in the melt pool, the thermal conductivity of the liquid has been increased by a factor of 3 [48].
Specific Heat and Latent Heat - The temperature-dependent specific heat of the alloy was defined as shown in Figure 4.4 (b). The latent heat associated with the solid/liquid phase transformation (286 kJ kg\(^{-1}\) [49]) was assumed to be released linearly between the solidus (1604 °C) and liquidus (1660 °C) temperatures. The release of latent heat during the \(\alpha/\beta\) phase transformation (48 kJ kg\(^{-1}\)) was also assumed to occur linearly between 800 °C and 1005 °C [49].

![Thermal Conductivity and Specific Heat](image)

Figure 4.4. Temperature-dependent a) thermal conductivity (k), and b) specific heat capacity (\(C_p\)) of Ti-6Al-4V alloy [12], [31], [50]

Elastic Modulus - The elastic modulus of Ti-6Al-4V powder was assigned a constant value of \(\frac{1}{10000}\) of the bulk material’s elastic modulus as approximated by Vastola et al. [12]. The
temperature-dependent elastic modulus of bulk Ti-6Al-4V alloy was available up to 1100 °C in the literature [51]. Beyond 1100 °C, it was extrapolated based on an approach adopted in references [15] and [48]. The approach used in this study is to assign a small value of 10 Pa for temperatures above the solidus temperature to limit stress accumulation in the liquid while maintaining convergence in the numerical model [48]. Therefore, the elastic modulus of Ti-6Al-4V was ramped down linearly from 18 GPa at 1100 °C to 10 Pa at the solidus temperature and held constant at 10 Pa beyond 1604 °C.

Yield Stress - The bulk yield stress values for Ti-6Al-4V are available in the literature for temperatures up to 910 °C. Above 910 °C, the bulk yield stress was assumed to decrease from 25 MPa to 15 MPa at the solidus temperature. A second linear decrease was also assumed from 15 MPa to 0.1 MPa at the mechanical coherency temperature (1609 °C). Finally, above 1609 °C, the yield stress was linearly increased to 10 MPa at 1660 °C based on the approach used by Sengupta et al. [29]. The increase in yield stress above the mechanical coherency point was done to avoid yielding and plastic strain accumulation in the material in the liquid state. A sensitivity analysis was performed to assess the assumptions described above. The sensitivity analysis results concluded that the objectives of minimizing stress and plastic strain accumulation in the semi-solid and liquid phases were achieved. The yield stress of the powder was assumed to be constant at 2 MPa based on the approach used in reference [12]. In addition, elastic perfectly-plastic behaviour was assumed in the model and the yield stress is independent of strain rate. A Von-Mises yield criterion has been used to determine the onset of the yielding.

The variation of elastic modulus and yield stress with temperature is shown in Figure 4.5 (a) and (b) respectively.
Figure 4.5. Mechanical properties of Ti-6Al-4V alloy (a) elastic modulus [6], [21], (b) yield strength [51]

**Thermal Expansion Coefficient** - Generally, the thermal strain is accumulated using an incremental formulation based on the tangent to the thermal expansion curve at \( T, \alpha'(T) \):

\[
\varepsilon(T) = \int_{T_0}^{T} \alpha'(T) dT
\]

Equation 4.4

where \( T_0 (\degree C) \) is the reference temperature for strain accumulation.
In this work, $T_0$ was set to the mechanical coherency temperature ($1609 \degree C$) of Ti-6Al-4V [52]. At temperatures above $1609 \degree C$, the thermal expansion coefficient was set to zero to avoid thermal strain generation in liquid. The thermal expansion coefficient of the powder was set to zero. This assumption is reasonable because negligible thermal stress is generated in the powder layer since it is composed of particles that expand and contract freely.

The UEXPAN subroutine was used for the thermal strain computation for two reasons: 1) to include the state variable (material form) dependence of the thermal expansion behaviour in the model, and 2) to zero the thermal strain in the powder and the consolidated material above $1609 \degree C$. The following incremental form of Equation 4.5 was used:

$$d\varepsilon^{th} = \alpha'(T)dT$$

Equation 4.5

where $d\varepsilon^{th}$ and $dT$ are the increments of thermal strain and temperature, respectively. The coefficient of thermal expansion for consolidated material was taken from the literature [17] up to $1609 \degree C$. The variation of the differential thermal expansion coefficient of Ti-6Al-4V alloy with temperature is shown in Figure 4.6 (a).

The variation of the Poisson ratio with temperature, shown in Figure 4.6 (b), is based on data reported in the literature [12], [40].
Figure 4.6. Mechanical properties of Ti6Al4V alloy (a) differential thermal expansion coefficient, (b) Poisson’s ratio [6]

4.1.6 Initial Conditions

The initial temperature of the substrate was set to the mechanical coherency point of the Ti-6Al-4V alloy (1609°C). In the first step of the analysis, the substrate is cooled down from an initial temperature of 1609 °C to $T_{\text{substrate}}$ (initially assumed to be 682 °C). This step is necessary to establish a state of thermal strain in the substrate material at $T_{\text{substrate}}$, and create an initial temperature gradient in the substrate. In this analysis, the substrate represents the previously deposited layers of the same material. The initial temperature of the powder layers when activated was set to a temperature of 25 °C. A detailed description of the different load steps involved in this analysis will be presented in section 4.1.7.

4.1.7 Thermal Boundary Conditions

A schematic diagram of the thermal boundary conditions is shown in Figure 4.7.

**Adiabatic Boundaries** – An adiabatic boundary condition was assigned to all of the analysis domain’s vertical surfaces, including the symmetry surface.

**Non-Adiabatic Boundaries** - A surface radiation boundary condition was applied to the top surface of each newly activated powder layer during the layer addition step as described in Equation 4.6.

$$q_{\text{rad}} = \varepsilon \sigma (T_{\text{int}}^4 - T_{\infty}^4)$$

Equation 4.6
where $\sigma$ is the Stephan Boltzmann constant ($5.67 \times 10^{-14}$ W m$^{-2}$ K$^{-4}$), $\varepsilon$ is the emissivity $= 0.3$, $T_\infty$ (°C) is ambient temperature, and $T_{\text{int}}$ (°C) is the instantaneous temperature of the top layer. The emissivity of both powder and bulk material was assumed to be 0.3 taken from the literature [12]. The radiation boundary condition was deactivated when the next powder layer was added.

A surface film condition, as described in Equation 4.7, was assigned to the bottom of the substrate (XZ surface) to simulate heat conduction to fictitious material extending beyond the bottom of the substrate.

$$q = h(T_s - T_{FM})$$

Equation 4.7

where $q$ (W mm$^{-2}$) is the surface flux, $h$ (W mm$^{-2}$ K$^{-1}$) is the heat transfer coefficient, $T_s$ (°C) is the surface temperature of the bottom of the domain, and $T_{FM}$ (°C) is the temperature of the fictitious material. This boundary was defined to drive the substrate temperature and powder to a prescribed temperature following the transit of the beam down the length of the domain. For example, $T_{FM}$ could be set to typical powder bed temperatures in an ARCAM EB-PBF system [31].

The heat transfer coefficient ($h$) was calculated using the heat balance equation shown in Equation 4.8 to allow a temperature gradient across the substrate to be defined as a simulation parameter.

$$h = \frac{-k \frac{\partial T}{\partial y}}{(T_{\text{substrate}} - T_{FM})}$$

Equation 4.8

where $k$ (W mm$^{-1}$ K$^{-1}$) is the thermal conductivity (0.015 W mm$^{-1}$ K$^{-1}$) and $\frac{\partial T}{\partial y}$ (°C mm$^{-1}$) is a specified temperature gradient in the $Y$ direction. For example, setting a 2 °C drop in temperature over the 0.8 mm height of the solid substrate and setting $T_{\text{substrate}} = 682$ °C and $T_{FM} = 670$ °C results in $h = 0.004$ W mm$^{-2}$ K$^{-1}$.
4.1.7.1 Heat Source Definition

The DFLUX subroutine was used to define the heat input distribution associated with the electron beam on the top surface of each newly activated powder layer. The expression used is based on a normal distribution, as shown in Equation 4.9 and Equation 4.10. The heat input was applied as a surface heat flux and moved from the left to right of the domain along the x-axis, as shown in Figure 4.7.

\[ q_{beam}(x, z, t) = \eta_e \eta_c P \left( \frac{1}{2\pi \sigma_{beam}^2} \exp \left( -\frac{(x-x_0(t))^2 + z^2}{2\sigma_{beam}^2} \right) \right) \]  \hspace{1cm} \text{Equation 4.9}

\[ x_0(t) = vt - 3\sigma_{beam} \]  \hspace{1cm} \text{Equation 4.10}

where \( q_{beam}(x,y,z,t) \) (W mm\(^{-2}\)) is the heat flux, \( P \) (W) is the beam power, \( \eta_e \) is the electron beam efficiency, \( \eta_c \) is the efficiency value for energy conversion at the part surface [12], [31], \( \sigma_{beam} \) (mm) is the standard deviation of the beam, \( x_0 \) (mm) is the X coordinate of the beam center, \( v \) (mm s\(^{-1}\)) is the beam speed, and \( t \) (s) is the current value of the total time.

The beam-related parameters used in the preliminary analysis were based on those reported by Jamshidinia et al. [31], and Vastola et al. [12] and are shown in Table 4.1. Since the domain is symmetric along the XY plane, only half of the electron beam distribution was included in the analysis.
### Table 4.2. Beam Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating voltage</td>
<td>60 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>14 mA</td>
</tr>
<tr>
<td>Beam efficiency $\eta_e$</td>
<td>0.85</td>
</tr>
<tr>
<td>Beam sigma</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Scan speed, $v$</td>
<td>500 mm s⁻¹</td>
</tr>
<tr>
<td>Energy conversion efficiency, $\eta_c$</td>
<td>0.24</td>
</tr>
</tbody>
</table>

#### 4.1.8 Mechanical Boundary Conditions

The mechanical boundary conditions were applied to approximate the mechanical constraints imposed by the surrounding previously deposited material. A schematic representation of the mechanical boundary conditions is shown in Figure 4.8. The rotational and translational boundary conditions are indicated by blue and orange markers, respectively. The symmetry boundary condition applied to the front XY surface of the domain is of the form:

$$ZSYMM: U_3 = UR_1 = UR_2 = 0$$

Equation 4.11

where $U_3$ is the displacement along the Z direction, $UR_1$ and $UR_2$ are rotational displacements about the X and Y directions, respectively.

The bottom surface of the domain was constrained in the Y direction to prevent vertical movement of the component as given by the following equation:

$$U_2 = 0$$

Equation 4.12

where $U_2$ is the displacement in the Y direction.

The entire YZ surface on the left side ($X = 0$) of the domain was restricted in the X direction to prevent rigid body motion, i.e.,

$$U_1 = 0$$

Equation 4.13

where $U_1$ is the displacement in the X-direction.

The XY plane opposite the symmetry boundary is assumed to be unconstrained, which may represent an under-constrained condition and should be noted in the interpretation of the results.
4.1.9 Analysis Configuration

The analysis steps used in the model are shown in Table 4.3, together with the time spent in each step. The first step was used to describe the evolution in substrate temperature as the substrate is cooled down from an initial temperature of 1609 °C to $T_{\text{substrate}}$ (initially set at 682 °C). This step is necessary to create the state of thermal strain in the substrate material at $T_{\text{substrate}}$, and establish the initial temperature in the substrate. The substrate temperature of 682 °C was chosen in this model to replicate the initial temperature condition of the experimental studies of Jamshidinia et al. [31]. As a reminder, the substrate material represents previously consolidated layers of powder. Therefore, this step was run once at the beginning of the analysis.

Steps 2 through 4 are repeated for each layer of powder added to the domain. Step 2 is the powder activation stage, in which the layer is activated and the radiation boundary condition on the top surface is activated. In this step, the material properties in the activated layer and the boundary conditions are “ramped on” as described in the ABAQUS user manual. Step 3 described the motion of the beam down the length of the domain, allowing heating and melt sintering of the powder to occur. In Step 4 (cooling step), the newly deposited layer (both melt sintered material and unsintered powder) is allowed to thermally equilibrate with the substrate. Sufficient time, 0.6 s, is given to allow the active elements in the domain to approximately reach $T_{\text{substrate}}$, prior to activation of the next layer. The total analysis time (including the layer addition, heating, and...
cooling steps) was ~4.06 s. The computational time of the analysis when using 10 parallel processors was ~120 hours.

The initial, minimum, and maximum time step values for the four steps of the analysis are listed in Table 4.4. The integration time step for all the steps was set to be automatically chosen by ABAQUS within the range shown in Table 4.4. The maximum temperature change in an increment was set to 10 °C.

Table 4.3. Steps defined for the first layer

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Name / Description</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial cooling / The substrate is cooled from an initial temperature of 1609 °C to 682 °C</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>Powder activation / Powder addition and heating (cooling of the substrate)</td>
<td>0.0001</td>
</tr>
<tr>
<td>3</td>
<td>Beam movement / Melt/Sintering</td>
<td>0.015</td>
</tr>
<tr>
<td>4</td>
<td>Layer Cooling / Cooling the layer to 682 °C</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 4.4. Time step values

<table>
<thead>
<tr>
<th>Step number</th>
<th>Description</th>
<th>Initial Time Step (s)</th>
<th>Minimum Time Step (s)</th>
<th>Maximum Time Step (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial cooling</td>
<td>$10^{-5}$</td>
<td>$10^{-15}$</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Powder Activation</td>
<td>$10^{-6}$</td>
<td>$10^{-25}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Layer Cooling</td>
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<td>$10^{-15}$</td>
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</table>
Chapter 5: Results and Discussion

The numerical results of the analysis are presented and discussed in this chapter. In addition, the effect of the various processing parameters on the evolution of stress and strain in the EB-PBF process is also studied.

5.1 Model Validation

To validate the model, the melt pool depth and width obtained from the model were compared to experimental and model predictions obtained from a study conducted by Jamshidinia et al. [31]. Jamshidinia et al. performed the study on an EB-PBF using a Ti6Al4V alloy. The melt pool dimensions were measured with a two-axis optical non-contact profilometer (Nanovea PS50 profilometer). The model was run using identical process conditions (power, scan speed, efficiencies) to those used in Jamshidinia et al.’s study (refer to Table 4.2).

The contour plot presented in Figure 5.1 shows the nodal temperature distribution in a subsection of the domain at 0.008 s during the processing of the first layer. At 0.008 s, the beam has travelled approximately halfway down the length of the domain on the first powder layer and reached a stable depth and width. Note: the limited amount of heat transport normal to the beam path in the time taken for the melt pool to solidify.

![Nodal Temperature Distribution](image)

Figure 5.1. Nodal temperature distribution at 0.008 s when the beam is halfway in the domain

*Figure 5.2 shows a contour image of the predicted temperature at 0.008 s during the processing of the first layer with a minimum temperature limit of 1604 °C (solidus temperature) to graphically highlight the melt pool dimensions. Figure 5.3 compares the current model predicted melt pool dimensions with the dimensions obtained from Jamshidinia et al.’s [31] work. As can*
be seen, there is good agreement between the model results and the data obtained from the literature.

Figure 5.2. (a) Melt pool length and depth, (b) Melt pool half-width

Figure 5.3. Comparison of (a) length, (b) width, (c) depth of melt pool of the base case with [44]
5.2 Discussion

The results of the meso-scale model predictions will now be considered in more detail. To begin, the temperature, stress, and plastic strain results will be reviewed to highlight the key phenomena that occur. The results of the mechanical analysis focus on the axial component of stress (S11) and axial component of strain (PE11), as previous work has shown them to be of the largest magnitude [28]. Contour plots of the temperature (NT11), the normal stress in the X-direction (S11), and the plastic strain in the X-direction (PE11) at selected times during the melting/sintering (Step 3) and layer cooling (Step 4) stages of the process are presented in Figure 5.4, Figure 5.5, Figure 5.6 respectively, for each of the 4 powder layers. In each series of plots, labels (a), (c), (e), and (g) present the contour plot when the beam is located approximately at the centre of the domain, and labels (b), (d), (f), (h) display the contour plot at the end of the cooling step just before adding the next powder layer.

Referring to Figure 5.4 (a) the melt pool is delineated by the liquidus and the solidus lines (light grey and black isotherm lines, respectively). At this location in the domain, the melt pool has achieved a pseudo-steady-state depth, width, and length. The domain was chosen to be of sufficient length to allow this to occur. A region of heated powder and substrate can be seen extending in front of, beside, behind, and below the beam centre. The motion of the beam creates steeper temperature gradients ahead of the beam than behind due to the relatively slow rate of heat diffusion compared to the beam speed. The light blue contour ahead of the beam indicates that the cold powder layer has not reached the same temperature as the substrate despite diffusional heat exchange between the relatively hot substrate and the cold powder. The ‘quenching’ effect of the powder can be seen extending well into the substrate.

Figure 5.4 (b) shows the thermal contour at the end of the cooling period following the melt/sintering step. As can be seen, the large thermal gradient associated with the intense heating by the beam has dissipated, and the domain reaches a relatively uniform temperature. The process described above consistently occurs in association with the analysis of powder layers 2 through 4, as shown in Figure 5.4 (c) to (h). A large zone of compression can be seen to develop below the melt pool in Figure 5.5 (a), (c), (e), and (g). Note that the stress is zero in the powder and the melt pool due to the mechanical properties assigned to the liquid and the powder in the model, consistent with expectations. After cooling, a large zone of tension (30 to 110 MPa) forms in the zone surrounding the beam path that extends down into the substrate and builds in-depth with the
addition of each powder layer – see Figure 5.5 (b), (d), (f), and (h). The zones of tension seen in Figure 5.5 (b), (d), (f), and (h) are present when the substrate and the powder layer are essentially isothermal (refer to Figure 5.4), which indicates that the stress is associated with the area of residual compressive plastic strain.
Figure 5.4. The nodal temperature contour plots at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer.
Layer number
Step 3 (melting/sintering)  
Step 4 (cooling of the layer)

Layer 1

(a) Step time = 0.008 s
(b) Step time = 0.6 s

Layer 2

(c) Step time = 0.008 s
(d) Step time = 0.6 s

Layer 3

(e) Step time = 0.008 s
(f) Step time = 0.6 s

Layer 4

(g) Step time = 0.008 s
(h) Step time = 0.6 s

Figure 5.5. The normal stress in the X direction (S11) contour plot at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer

44
As shown in Figure 5.6 (a), a zone of compressive plastic strain forms below and in the wake of the melt pool. The same pattern of plastic strain development is observed in Figure 5.6 (c), (e), and (f). This zone forms due to the rapid heating and expansion of the material below the melt pool, which leads to the development of the large compressive stresses observed in Figure 5.5 (a), (c), (e), and (f). This zone can be seen extending into the substrate.

Figure 5.6 (b), (d), (f), and (h) show a zone of plastic strain associated with the beam path that is retained in the material after the cooling step, which is responsible for the tensile stress observed at the end of the cooling step. The magnitude of the plastic strain in these figures ranges from -0.0015 to -0.0022. To validate the predictions of plastic strain in the current work, data has been extracted from research done by Zhang et al. [28] on a laser powder bed fusion AM (L-PBF) process utilising Ti6Al4V. They report a plastic strain of -0.002 in the X-direction (PE11) in a thermo-elastoplastic simulation. The plastic strain is used in their work to capture the local strain developed in proximity to the melt pool, which can be used in a macro scale thermo-mechanical model. As indicated above, the strain range of -0.0015 to -0.0022 predicted in the current work utilising a mesoscale model is consistent with the plastic strain in the X direction used by Zhang et al. [28], albeit for a different AM process.
Layer number | Step 3 (melting/sintering) | Step 4 (cooling of the layer)
---|---|---
Layer 1 | ![Image](image1.png) (a) Step time = 0.008 s | ![Image](image2.png) (b) Step time = 0.6 s
Layer 2 | ![Image](image3.png) (c) Step time = 0.008 s | ![Image](image4.png) (d) Step time = 0.6 s
Layer 3 | ![Image](image5.png) (e) Step time = 0.008 s | ![Image](image6.png) (f) Step time = 0.6 s
Layer 4 | ![Image](image7.png) (g) Step time = 0.008 s | ![Image](image8.png) (h) Step time = 0.6 s

Figure 5.6. The X-component of plastic strain (PE11) profiles at (a) 0.008 s and (b) 0.6 s first layer; (c) 0.008 s and (d) 0.6 s second layer; (e) 0.008 s and (f) 0.6 s third layer; and (g) 0.008 s and (h) 0.6 s fourth layer
To summarise, when the beam heats the domain, large thermal gradients are generated by intense heating, resulting in the development of large thermal stresses. This, in turn, leads to yielding and plastic strain accumulation. Finally, when the component is cooled down, the residual plastic strain generates residual stresses in the component.

*Figure 5.7 shows the distribution of the variable defining the state of the material (e.g., bulk or powder) at the end of processing the fourth layer. As can be seen, the material that has been heated above the liquidus temperature has been assigned a value of 1, indicating that the powder has been transformed into bulk material in terms of its material properties.*

![SDV1 (Avg: 75%)](image)

**Figure 5.7. The distribution of state variable in the domain at the end of processing the fourth layer.**

To further investigate the development of stress and strain in the vicinity of the melt pool, data has been extracted from the model at two locations (elements A and B) as a function of time. As shown in *Figure 5.8*, element A lies on the top surface of the first powder layer, and element B is in the substrate, 0.3 mm below element A and approximately three elements below the substrate-powder layer interface.
Figure 5.8. The contour plot of normal stress in the X-direction (S11) in MPa at 0.008 s highlighting the location where quantitative data has been extracted from the model.

The normal stress evolution in the X-direction (S11) with time during the melting/sintering step (Step 3) in elements A and B have been plotted in Figure 5.9 (a) and (b), respectively, together with the evolution in temperature. Figure 5.10 (a) and (b) show the evolution of plastic strain in the X-direction as a function of time and temperature. Note, time 0 in Figure 5.9 and Figure 5.10 corresponds to the end of the cooldown step (step 1 – refer to Table 4.3) for the first powder layer, which is 1.6 s into the overall simulation time. The solidus and liquidus lines are added to the plots to aid in identifying when solidification starts and finishes at locations A and B. In addition, a shaded region has been added to the plots, highlighting the time required for the electron beam to transit across the location of elements A and B. The beam entrance and exit times were defined in terms of ± 3σbeam of the beam centre.
As was described in the initial conditions section and shown in Figure 5.9 (a), the powder is added to the domain at 25 °C. Before the beam reaches element A, the temperature of the powder increases because of contact with the hot substrate. At this stage, virtually no stress is generated since the material is in powder form, consistent with the material properties input to the model. As the beam reaches element A, the powder is rapidly heated to a temperature (~ 2188 °C) above the liquidus. Again, the material develops negligible stress at this stage, consistent with the material properties defined for the liquid. When the beam moves past element A, the material rapidly cools...
and enters a compressive stress state (reaching a minimum of ~ -4.7 MPa). As it continues to cool, the state of stress transitions to tension and gradually increases to ~ 12 MPa.

Shifting the focus to element B, the substrate is cooled from the initial temperature of 682 °C due to contact with the cold powder. The temperature gradient that develops in the substrate results in the material in element B experiencing a state of tension, reaching a peak of ~ 130 MPa. As the temperature gradients near the powder and substrate interface moderate, the tensile stress gradually drops to ~65 MPa before the beam arrives above element B. When the beam reaches element B, the material heats rapidly, placing it into a state of compression (~ -23 MPa). Shortly after the beam moves past element B, the material transitions back to a state of tension as it cools down, reaching ~ 16 MPa at 0.015 s.
Figure 5.10. Variation of plastic strain (PE11) and temperature in (a) Element A and (b) Element B (see locations in Figure 5.8) with time during melting of the first powder layer.

The evolution in plastic strain in the X-direction (PE11) at elements A and B is shown in Figure 5.10 (a) and (b), respectively. Starting with element A, no strain is accumulated in the powder layer as it is heated by the beam and melted, consistent with the material properties input to the model. As the beam moves past element A, the material cools and solidifies and transitions to a state of compressive stress for a short period (reaching a minimum of -4.7 MPa). During this time, the material accumulates compressive plastic strain, reaching a minimum of ~ -0.005, as observed in Figure 5.10 (a). As the stress state of the material transitions back into tension, the
magnitude of the compressive plastic strain gradually reduces, reaching a value of -0.0025 at 0.014 s.

*Figure 5.10 (b)* shows the evolution of plastic strain in the X-direction (PE11) in element B. As the beam reaches a location above element B, the material is rapidly heated and the stress state transitions from tension to compression, reaching a minimum of -23 MPa. The transition from tensile to compressive stress at an elevated temperature result in the accumulation of a compressive plastic strain of -0.0047. As the beam leaves the region above element B, the material accumulates further plastic strain reaching a minimum of -0.0055. Finally, the stress state of the material transitions back into tension as it cools, and the compressive plastic strain reduces (reaching -0.0023 at 0.015s).

To summarize, *Figure 5.9* and *Figure 5.10* show dynamic behaviour concerning the rapidly changing temperature, thermal stress, and strain fields in both the powder and substrate material as the beam moves through a given area of the domain. The rapid heating associated with the beam leads to the generation of compressive stresses in the vicinity of the melt pool in both the powder and substrate. As the stresses develop at an elevated temperature, the material accumulates plastic strain, as its yield strength is very low. Therefore, the high-temperature constitutive behaviour must be properly described. Having completed the analysis for a single powder layer, the focus is now shifted to considering the effect of adding multiple layers of powder. *Figure 5.12* and *Figure 5.11* show a series of contour plots of plastic strain (PE11) and stress (S11), respectively, after cooling the domain to 682 °C (analysis step 4). Note that the domain is nearly isothermal at this point in the analysis (see *Figure 5.4*); hence, the residual plastic strain in the component is what drives the stress evolution. The contour images are on the YZ plane approximately at mid-length in the domain. Labels (a) through (d) in *Figure 5.12* and *Figure 5.11* show the results after 1, 2, 3, and 4 layers of powder have been added.
According to Figure 5.12, a zone of compressive strain builds vertically as the new layers are added. The plastic strain after layer 1 is deposited and cooled varies from -0.0017 to -0.0019 and this increases to a range of -0.0022 to -0.0025 in layer 4. The regions experiencing tensile stress shown in Figure 5.12 can be directly linked to the regions exhibiting compressive plastic strain in Figure 5.12. As can be seen, the areas in each new layer in which powder has been melt/sintered are in a state of tension after cooling (in the range of 96 to 116 MPa). Consequently, there is a vertical (in the Y-direction) zone of tensile stress associated with multiple beam passes. The tensile stress region in the substrate extends down (in the Y-direction) and outward (in the Z-direction) and is larger in size than predicted in the powder layer. These regions represent material that has been compressed and yielded. As the domain cools in step 4 and transitions to an isothermal state, the material exhibiting residual compressive plastic strain is placed into a tensile stress state as the forces within the structure re-equilibrate.
Figure 5.12. Stress (S11) profile (MPa) on cooling the 1st, 2nd, 3rd, and 4th layers to the substrate temperature on the YZ surface.

To take a more quantitative look at the distribution of plastic strain (PE11) and stress (S11) as the layers are incrementally added to the domain, data has been extracted from the model and plotted along a vertical line (in the Y-direction shown in Figure 5.11 (d)) from the bottom of the substrate to the top of the last layer added to the domain (see Figure 5.13 (a) and (b)). The vertical line at 0.8 mm indicates the boundary between the layers added to the domain and the substrate. Figure 5.13 (a) shows three zones exhibiting different behaviours: 1) a zone of virtually no plastic strain in the substrate between 0 to 0.4 mm, 2) a zone of increasing compressive plastic strain in the substrate between 0.4 to 0.6 mm, and 3) a zone of varying compressive plastic strain in the layers and the substrate above 0.6 mm. The magnitude of PE11 in the third zone after processing the first layer remains largely constant at -0.0017. With the addition of layers 2, 3, and 4, a slight increase in the magnitude of PE11 can be observed, reaching a peak of -0.0022 after processing the fourth layer.

Figure 5.13 (b) shows three zones exhibiting different behaviours: 1) between 0 to 0.4 mm, the substrate is under relatively uniform compressive stress ranging from ~ -44 MPa following the addition of the first layer to ~ -54 MPa after the addition of the last layer, 2) between 0.4 to 0.6 mm, the substrate transitions to a tensile state of stress, and 3) a region of relatively constant tensile stress forms in the substrate and the layers, ranging from 94 to 114 MPa above 0.6 mm.
Effect of Parameters

After evaluating the stress and strain fields with the preliminary processing conditions, calculations were performed to study the effect of the varying (a) substrate temperature, (b) beam power, and (c) beam scanning speed.

5.3.1 Substrate Temperature

Two different substrate temperatures (630 °C and 730 °C) were input to the model while holding the remaining process parameters identical to the base case (500 mm s⁻¹ scanning speed and 840 W power), and the results were compared to the base case (substrate temperature = 682 °C). Figure 5.14 shows the effect of substrate temperature on the plastic strain (PE11) and stress (S11) profiles along a vertical line (in the Y-direction) from the bottom of the substrate to the top.
of the fourth layer. The vertical line added to each graph at 0.8 mm indicates the boundary between the layers added to the domain and the substrate. Note that the domain is isothermal at this point in the analysis. It can be observed that a decrease in the substrate temperature results in a substantial increase in compressive plastic strain (PE11) and stress (S11) in the layers and the substrate above 0.6 mm. For example, a decrease in substrate temperature from 682 °C to 630 °C increased the peak compressive plastic strain (PE11) from -0.0022 to -0.003. Additionally, the peak stress (S11) increased from 100 MPa to 155 MPa. This effect is the opposite when the substrate temperature increases. Furthermore, with a decrease in the substrate temperature, the depth of the compressive plastic strain zone in the substrate slightly decreases; therefore, the depth of the zone in the substrate under tensile stress also decreases. This effect is opposite and more pronounced when the substrate temperature is increased. This is because increasing and decreasing the substrate temperature affects the thermal gradient during heating, which is the driving force for the development of plastic strain and, ultimately, the residual stresses. The numerical calculations are consistent with the studies done by Vastola et al. [12] and Beuth et al. [53].
Figure 5.14. Effect of substrate temperature on the vertical profile of (a) plastic strain (PE11) and (b) stress (S11) after processing and cooling the fourth layer. Note that the data has been extracted from the centroid of each element.

5.3.2 Change of Beam Power

Two different beam powers (740 and 940 W) were input to the model while holding the remaining process parameters identical to the base case (500 mm s\(^{-1}\) scanning speed and 682 °C substrate temperature), and the results were compared to the base case (beam power = 840 W). *Figure 5.15* shows the effect of beam power on the plastic strain (PE11) and stress (S11) profiles using the same format as previously described. It can be observed that increasing the beam power results in a substantial increase in the depth of the compressive plastic strain zone in the substrate, whereas a reduction in the beam power did not alter the distribution of the plastic strain in the substrate. Furthermore, as the beam power increases, a decrease in the magnitude of compressive
plastic strain (PE11) and an increase in stress (S11) in the layers can be observed. For example, an increase in the beam power from 840 to 940 W decreases the peak compressive plastic strain (PE11) from -0.0023 to -0.0021, leading to an increase in the peak tensile stress (S11) from 115 to 124 MPa. The relationship between plastic strain and stress observed when the power increases are opposite to that observed when the substrate temperature is altered (i.e., a decrease in the strain in the layers results in an increase in the tensile stress). The reason for this is unclear but may be related to the substantial increase in the depth of the compressive strain zone in the substrate.

![Graph](image)

Figure 5.15. Comparison of the vertical profile of (a) plastic strain (PE11) and (b) longitudinal stress (S11) on cooling the four layers to the substrate temperature for different values of beam power
5.3.3 Beam Speed

Two different beam speeds (300 and 700 mm s\(^{-1}\)) were input to the model while holding the remaining process parameters identical to the base case (682 °C substrate temperature and 840 W power), and the results were compared to the base case (beam speed = 500 mm s\(^{-1}\)). Figure 5.16 shows the effect of beam speed on the stress (S11) and plastic strain (PE11) profile along the vertical line with the same format described in the previous two sections. It can be observed that increasing the beam speed results in an increase in the magnitude of compressive plastic strain (PE11) and stress (S11) in the layers and decreasing the beam speed results in a decrease in the magnitude of plastic strain (PE11) and stress (S11) in the layers. For example, an increase in the beam speed from 500 to 700 mm s\(^{-1}\) increased the peak compressive plastic strain (PE11) from -0.0022 to -0.0024, resulting in an increase in peak stress (S11) from 104 to 144 MPa. Furthermore, with an increase in the beam speed, the depth of the compressive plastic strain zone in the substrate decreases. The relationship between the residual compressive plastic strain and stress, in this case, is similar to that observed when altering the substrate temperature. As noted previously, the opposite trend was observed in the case of beam power.
Figure 5.16. Comparison of the vertical profile of (a) plastic strain (PE11) and (b) longitudinal stress (S11) on cooling the four layers to the substrate temperature for different values of beam speed.

*Table 5.1* summarises the sensitivity analysis results for the X-component of plastic strain (PE11) to substrate temperature, beam power, and beam speed obtained from the mesoscale analysis. For completeness, the plastic strain in the other two orientations is also included. In this Table, the plastic strain (PE11) is presented for each layer with an overall average value for the four layers. For PE22 and PE33 only the average is presented. Note that to conserve volume the sum of the three normal plastic strains should approximately be equal to zero.

*Table 5.1* may be used in a macroscale thermal-stress analysis as a look-up table, providing the inherent plastic strain as a function of the two process parameters (beam power and beam speed) and the substrate temperature. In this approach, the substrate temperature would represent
the temperature of the previously consolidated layer directly beneath the newly added layer at the location being processed in a macroscale thermal stress analysis.

Table 5.1. A look-up table showing the effect of different processing conditions on the magnitude of the plastic strain PE11 after cooling the deposited layers to the substrate temperature

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<th>Unchanged Parameters</th>
<th>Varying Parameter</th>
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<th>Layer deposited</th>
<th>PE11 (layer)</th>
<th>Average PE11</th>
<th>Average PE22</th>
<th>Average PE33</th>
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</table>
As a final step, the results from this work have been compared to published data. Two studies [28], [44] have been identified in the literature in which plastic strain data in the direction of the scanning path has been presented for the L-PBF process. In one study, data was presented for a scanning speed of 1000 mm s\(^{-1}\) and the other study for 1250 mm s\(^{-1}\). Both studies use a laser power of 200 W; however, the efficiency and substrate temperature was not reported.

The data from Zhang et al. and Siewert et al.’s articles have been presented in Figure 5.17, together with the predictions from the mesoscale model for scanning speeds of 300, 500, 700, 1000, and 1250 mm s\(^{-1}\) using a substrate temperature of 682 °C. Additionally, mesoscale model predictions for substrate temperatures of 630 and 730 °C at 1000 and 1250 mm s\(^{-1}\) have been included in the plot. All the model predictions reported in this analysis had a beam power of 840 W, an electron beam efficiency of 0.85, and an energy conversion efficiency at the part surface of 0.24. As can be seen, the results are in relatively good agreement with the published data on the L-PBF process, given that the results are for a different AM process and there is missing information in these studies (e.g., the substrate temperatures and the beam efficiency).

![Figure 5.17. Comparison of the plastic strain (PE11) model predictions (EB-PBF) with literature results [18], [27]](image-url)
Chapter 6: Conclusion and future scope of work

6.1 Summary

In conclusion, a comprehensive mesoscale, thermal-stress model has been developed for investigating the plastic strain and stress evolution during the melting and solidification of Ti6Al4V alloy in an EB-PBF process. The analysis has been done for four powder layers additions to a substrate. In each powder layer, the beam scans a single track, and the tracks are located directly above one another. The model allows for exploring the effect of substrate temperature and the rate of heat removal from the substrate on the strain and stress fields within the domain. The model was developed using a base case set of parameters, including a substrate temperature of 682 °C, a beam power of 840 W, and a scanning speed of 500 mm s\(^{-1}\).

Two common challenges associated with formulating the constitutive behaviour of the material in powder and bulk forms were resolved. The first entailed capturing the transition in properties from the powder form to the bulk form, which was resolved by defining a state variable and linking it to the material form. In this approach, the state variable was set to 0 for the material when it was considered to be powder. The state variable was linearly varied between 0 and 1 between the solidus and the liquidus temperatures. When the state variable is equal to 1, the materials are considered to have properties consistent with the bulk form. The second was focused on describing the constitutive behaviour at elevated temperatures where experimental data was unavailable in the literature. The constitutive behaviour was described in a manner that avoided the accumulation of stress and plastic strain in the liquid.

The model results revealed a large band of compressive stress surrounding the melt pool as the beam was translated down the length of the domain. This band resulted in the formation of a band of compressive plastic strain. The stress and strain orientation with the largest magnitude was found to be the same as the beam trajectory direction (S11 and PE11). As the material cooled and became isothermal after each beam scan, the stress in areas under residual compressive strain transitioned into a tensile state.

A sensitivity analysis was conducted with the model to examine the effect of substrate temperature, beam power, and beam speed on the magnitude of stress following cooling of the domain to the substrate temperature. Increasing the substrate temperature from 682 to 730 °C resulted in reducing the compressive residual strain and the associated tensile stress. Conversely,
decreasing the temperature to 630 °C led to an increase in the magnitude of the compressive plastic strain and the associated tensile stress. Similarly, increasing and decreasing the scan speed (from 500 to 700 and 300 mm s⁻¹, respectively) had the same effect on the magnitude of the compressive plastic strain and the associated stress. However, the opposite trend was observed when increasing the beam power from 840 to 940W – e.g., the magnitude of the compressive plastic stress was decreased, whereas the tensile stress was increased.

6.2 Scope of future work

The present study focused on a fully coupled temperature displacement model to predict the stress and inelastic strain accumulation in the vicinity of the melt zone. Incorporating a broader range of beam properties and process parameters such as scanning speed, power, and substrate temperature by running more simulations in ABAQUS will help to populate the look-up table of equivalent plastic strains under diverse processing conditions.

Additionally, a mesoscale model can be developed using a commercial computational fluid dynamics (CFD) package to predict the heat transport phenomena in the EB-PBF process. The CFD approach can effectively incorporate phenomena such as preferential species evaporation, recoil pressure, buoyancy, Marangoni flow, buoyancy, and diffusion in the PBF process. A sequentially coupled model can be developed by combining the temperature history predicted by the heat transfer and fluid flow (CFD) model and an ABAQUS-based FE model to simulate the deposition of multiple powder layers. The transient temperature fields from the heat transfer and fluid flow model can be mapped to the mechanical model using the application programming interface (API) in ABAQUS. The FE model can give valuable insight into the distribution of stress and inelastic strain in the EB-PBF process and produce a look-up table of “equivalent plastic strains”.

A macroscale model can then be developed to capture the mechanical response of a part at an appropriate time and length scales by implementing the equivalent plastic strain data from the look-up table produced from the mesoscale model. The model predictions can be experimentally validated using samples produced with the EB-PBF system available at UBC.
References


thermstressanal.htm#hj-top.


Appendix

This appendix provides additional numerical results on the effect of the processing parameters. The results include the stress and strain contour profiles, nodal temperature contour plots, and the melt pool dimensions under variable beam power and scanning speed.

Figure A.1 shows the effect of substrate temperature on the x component of normal stress $S_{11}$ (MPa), and plastic strain $PE_{11}$ profiles when the fourth powder layer has cooled to its respective substrate temperatures. Two different substrate temperatures (630 °C and 730 °C) were input to the model while keeping the other process parameters consistent with the base case (500 mm s$^{-1}$ scanning speed and 840 W power), and the results were compared to the base case (substrate temperature = 682 °C). These contours are on the YZ plane approximately at mid-length in the domain (selected in Figure 5.8). Note that the domain is isothermal at this point in the analysis; hence, the residual plastic strain in the component is what drives the residual stress. It can be observed that a decrease in the substrate temperature results in a substantial increase in compressive plastic strain ($PE_{11}$) and stress ($S_{11}$) in the layers and the substrate. This effect reverses when the substrate temperature increases. Furthermore, with a decrease in the substrate temperature, the depth of the compressive plastic strain zone in the substrate slightly decreases; therefore, the depth of the zone in the substrate under tension.
Figure A.1. Contour plots (YZ surface) show the effect of substrate temperature on (a) longitudinal stress S11 (MPa), (b) plastic strain (PE11) when the four added layers are cooled down to the substrate temperature.

The nodal temperature contour plots and comparison of the dimensions of the melt pool with the variation of beam power are presented in Figure A.2 and Figure A.3 respectively. Two different beam powers (740 and 940 W) were input to the model while holding the remaining process parameters identical to the base case (500 mm s\(^{-1}\) scanning speed and 682 °C substrate temperature), and the results were compared to the base case (beam power = 840 W). It is seen that with the increase of beam power, the length, width, and depth of the melt pool increase in magnitude. The temperature of the beam center increases from 2110 °C to 2741 °C as the beam power rises from 740 W to 940 W. In addition, the length of the melt pool increases from 1.27 mm to 1.9 mm; the breadth changes from 0.65 mm to 0.76 mm, and the depth increases from 0.116 mm to 0.177 mm respectively during the increase of the beam power from 740 W to 940 W.
Figure A.2. Melt pool contours for (a) 740 W (b) 840 W (c) 940 W beam power

Figure A.3. Comparison of melt pool dimensions (a) Length, (b) Width, (c) Depth for different beam powers

Figure A.4 (a) and (b) present the two-dimensional contour plots demonstrating the effect of beam power on the distribution of S11 and PE11, respectively, after cooling the four layers to substrate temperature. An increase in the beam power from 740 to 940 W decreases the peak
compressive plastic strain (PE11) from -0.0026 to -0.0021, leading to an increase in the peak tensile stress (S11).

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(a) S11 (MPa)

Figure A.4. Contour plots (YZ surface) showing the effect of beam power on (a) longitudinal stress S11 (MPa), (b) plastic strain (PE11) when the four added layers are cooled down to the substrate temperature.

The nodal temperature contour plots and comparison of the dimensions of the melt pool with the variation of beam scanning speed are presented in Figure A.5 and Figure A.6 respectively. Two different beam speeds (300 and 700 mm s\(^{-1}\)) were used for the sensitivity analysis while holding the remaining process parameters identical to the base case (682 °C substrate temperature and 840 W power), and the results were compared to the base case (beam speed = 500 mm s\(^{-1}\)). It is seen that the melt pool contour becomes longer and shallower when the speed is increased. The
model data was validated against the experimental results of Jamshidinia et al. [31] for the beam speeds of 300 and 500 mm s$^{-1}$. The results were found to be in good agreement.

Figure A.5. Melt pool contours highlighting the effect of the beam speed: (a) 300 mm s$^{-1}$, (b) 500 mm s$^{-1}$, (c) 700 mm s$^{-1}$

Figure A.6. Comparison of the dimensions of melt pool of the model prediction with literature results
Figure A.7 (a) and (b) present the two-dimensional contour plots demonstrating the effect of beam power on the distribution of S11 and PE11, respectively, after cooling the four layers to substrate temperature. It can be observed that increasing the beam speed results in an increase in the magnitude of compressive plastic strain (PE11) and stress (S11) in the layers and decreasing the beam speed results in a decrease in the magnitude of PE11 and S11 in the layers.

Output ↓ / Speed → 300 mm s⁻¹  500 mm s⁻¹  700 mm s⁻¹

(a) S11 (MPa)

(b) PE11

Figure A.7. Contour plots (YZ surface) showing the effect of beam speed on (a) S11 (MPa), (b) PE11 when the four added layers are cooled down to the substrate temperature.