Verifying predictive temperature gradients for an as-built additively manufactured part

Jared Stone

Follow this and additional works at: https://louis.uah.edu/uah-theses

Recommended Citation
Stone, Jared, "Verifying predictive temperature gradients for an as-built additively manufactured part" (2020). Theses. 342.
https://louis.uah.edu/uah-theses/342

This Thesis is brought to you for free and open access by the UAH Electronic Theses and Dissertations at LOUIS. It has been accepted for inclusion in Theses by an authorized administrator of LOUIS.
VERIFYING PREDICTIVE TEMPERATURE GRADIENTS FOR AN AS-BUILT ADDITIVELY MANUFACTURED PART

by

Jared Stone

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Engineering
in
The Department Mechanical Engineering
to
The School of Graduate Studies
of
The University of Alabama in Huntsville

Huntsville, Alabama
2020
In presenting this thesis in partial fulfillment of the requirements for a master's degree from The University of Alabama in Huntsville, I agree that the Library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by my advisor or, in his/her absence, by the Chair of the Department or the Dean of the School of Graduate Studies. It is also understood that due recognition shall be given to me and to The University of Alabama in Huntsville in any scholarly use which may be made of any material in this thesis.

(Student Signature)  4/16/2020
(Date)
THESIS APPROVAL FORM

Submitted by Jared Stone in partial fulfillment of the requirements for the degree of Master of Science in Engineering with an option in Mechanical Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Engineering with an option in Mechanical Engineering.

Dr. Judith Schneider - Professor - MAE

(Date)

Dr. Sherri L. Messimer - Associate Professor - ISE

3/16/20

Dr. Michael Banish - Associate Professor - CME

3/16/20

Dr. Keith Hollingsworth - Professor and Department Chair - MAE

Department Chair

Digitally signed by Shankar Mahalingam
DN: cn=Shankar Mahalingam, o=College of Engineering, ou=Dean, email=sm0026@uah.edu, c=US
Date: 2020.04.06 10:29:51-05'00'

Shankar Mahalingam
College of Engineering Dean

Digitally signed by David Berkowitz
DN: cn=David Berkowitz, o=University of Alabama in Huntsville, ou=Graduate Dean, email=berkowit@mail.uah.edu, c=US
Date: 2020.04.06 13:49:45-05'00'

David Berkowitz
Graduate Dean
ABSTRACT
The School of Graduate Studies
The University of Alabama in Huntsville

Degree____ Master of Science____ College/Dept. __ Mechanical Engineering ____________

Name of Candidate _______________ Jared Stone
Title: Verifying Predictive Temperature Gradients for an As-Built Additively Manufactured Part

Additive Manufacturing (AM) is a fabrication process that provides a cost effective alternative to conventional subtractive methods for small volume, complex parts. To accelerate development, numerical modeling methods are being evaluated to establish processing parameters thereby reducing the current trial and error methods. Resulting microstructure of an AM build is determined by the thermal profile it undergoes in-situ. This study uses a nominal approach to verify modeling predictions with metallurgical analysis of an as-built AM part. The finite difference additive thermal model (DATM) was used to construct temperature gradients from its generated temperature and time data simulated for a single bead plate build using 4340 steel. Predicted temperature gradients were overlaid onto time-temperature-transformation (TTT) and continuous cooling transformation (CCT) diagrams. Images from metallurgical evaluation of the actual build are compared with the predicted microstructures as a function of the cooling rate to verify results.

Abstract Approval: Committee Chair ________________________________
Department Chair ________________
Graduate Dean ________________________

David Berkowitz

iv
ACKNOWLEDGEMENTS

Funding was provided by the Navy STTR Phase II with Oregon State/Keystone Synergistic Enterprises, Inc., entitled “Real-Time AM Process Models Applied to Wire Fed Robotic Pulsed-Arc Processed 4340 Steel,” Contract #KSE17035-OIT.

The work described in this thesis would not have been possible without the assistance of several people who deserve special recognition. Firstly, I would like to thank Dr. Judy Schneider for her guidance and the opportunity given to me to engage actively in learning in both the classroom and lab setting. Your lessons will always be cherished. Second, Dr. Tom Stockman for his teachings and assistance that began my graduate school journey. Third, the members of my committee who have been very helpful with comments, suggestions, and encouragement.

I would like to thank my wife and son for their continued encouragement, support, love, and understanding who motivation for me were to begin my pursuit of this degree.
# TABLE OF CONTENTS

Page

List of Figures .................................................................................................................. viii

List of Tables ................................................................................................................... xiii

Chapter

1.0 INTRODUCTION ........................................................................................................ 1

1.1 Introduction to Additive Manufacturing ................................................................. 1

1.2 Microstructure Formation in Additively Manufactured Parts ............................... 3

1.3 Thermal Predictions in Additive Manufacturing ..................................................... 6

2.0 BACKGROUND INFORMATION .............................................................................. 9

2.1 Overview of DATM .................................................................................................. 9

2.2 Material - Alloy Steel 4340 .................................................................................... 10

2.3 Equilibrium Phases in 4340 Alloy Steel .................................................................. 12

2.4 Non-equilibrium Transformations Diagrams for 4340 ........................................... 15

3.0 EXPERIMENTAL PROCEDURE .......................................................................... 18

3.1 Build Plan for Single Pass Wall .............................................................................. 18

3.2 Cut Plan for Test Specimens .................................................................................. 19

3.3 Modeling Predictions ............................................................................................. 21

3.4 Experimental Procedure ......................................................................................... 23

3.4.1 Hardness Testing ............................................................................................... 23

3.4.2 Mechanical Properties ....................................................................................... 24
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Deposition rate vs. resolution of various metal additive manufacturing processes</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Wire fed arc additive manufacturing (WAAM) diagram</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Three major zones of a fusion weld</td>
<td>4</td>
</tr>
<tr>
<td>1.4</td>
<td>WAAM AM build orientations showing the build plane (XY) and build direction (Z)</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>Fe-C equilibrium phase diagram</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>Time-Temperature-Transformation diagram for 4340 alloy steel</td>
<td>15</td>
</tr>
<tr>
<td>2.3</td>
<td>Continuous-Cooling-Transformation diagram for 4340</td>
<td>17</td>
</tr>
<tr>
<td>3.1</td>
<td>Single-pass wall build plan (A) and pathing directions (B)</td>
<td>19</td>
</tr>
<tr>
<td>3.2</td>
<td>Tensile specimen dimensions in inches</td>
<td>20</td>
</tr>
<tr>
<td>3.3</td>
<td>Cut plan layout for the single pass 4340 alloy steel build</td>
<td>21</td>
</tr>
<tr>
<td>3.4</td>
<td>Specimen breakdown of the Z1 sample</td>
<td>24</td>
</tr>
<tr>
<td>4.1</td>
<td>DATM projection of cooling for initial layer with room temperature substrate</td>
<td>28</td>
</tr>
<tr>
<td>4.2</td>
<td>Cooling predictions for a bainite curve example with a TTT diagram for 4340</td>
<td>29</td>
</tr>
<tr>
<td>4.3</td>
<td>Cooling predictions for a bainite curve example with a CCT diagram for 4340</td>
<td>30</td>
</tr>
<tr>
<td>4.4</td>
<td>CCT predicted cooling rates when layers are initially deposited</td>
<td>32</td>
</tr>
<tr>
<td>4.5</td>
<td>CCT predicted single pass wall cooling rates when the layer above is deposited</td>
<td>33</td>
</tr>
</tbody>
</table>
4.6 CCT predicted single pass wall cooling rates when a second additional layer is deposited .................................................................34
4.7 DATM tempering predictions for the entire build..........................35
4.8 The Z1-1 sample ranging from the baseplate to layer 5 in the Z direction.........41
4.9 The Z1-2 sample going from layers 6 - 10 in the Z direction.........................43
4.10 The Z1-3 sample moving from layers 11 - 15 in the Z direction......................45
4.11 The Z1-4 sample from layers 16 - 20 in the Z direction......................47
4.12 The Z1-5 sample from layers 21 - 28 in the Z direction.................................49
4.13 SEM images of the lower, middle, and upper locations in the Z1-1 sample ....50
4.14 SEM images of the middle and upper locations of the Z1-5 sample .............52
A.1 TTT predicted single pass wall cooling rate for layer 1 ........................59
A.2 TTT predicted single pass wall cooling rate for layer 2 ..........................60
A.3 TTT predicted single pass wall cooling rate for layer 3 ............................60
A.4 TTT predicted single pass wall cooling rate for layer 4 .............................61
A.5 TTT predicted single pass wall cooling rate for layer 5 .............................61
A.6 TTT predicted single pass wall cooling rate for layer 6 .............................62
A.7 TTT predicted single pass wall cooling rate for layer 7 and 8.................62
A.8 TTT predicted single pass wall cooling rate for layer 9 ..............................63
A.9 TTT predicted single pass wall cooling rate for layer 10 ..........................63
A.10 TTT predicted single pass wall cooling rates for layers 11 and above ...............64
A.11 TTT predicted single pass wall cooling rate for layer 1 after two additional layers are deposited ..........................................................64
A.12 TTT predicted single pass wall cooling rate for layer 2 after two additional layers are deposited ........................................................................65
A.13 TTT predicted single pass wall cooling rate for layer 3 after two additional layers are deposited ........................................................................65
A.14 TTT predicted single pass wall cooling rate for layer 4 after two additional layers are deposited ........................................................................66
A.15 TTT predicted single pass wall cooling rate for layer 5 after two additional layers are deposited ........................................................................66
A.16 TTT predicted single pass wall cooling rate for layer 6 after two additional layers are deposited ........................................................................67
A.17 TTT predicted single pass wall cooling rate for layer 7 and 8 after two additional layers are deposited ........................................................................67
A.18 TTT predicted single pass wall cooling rate for layer after two additional layers are deposited ........................................................................68
A.19 TTT predicted single pass wall cooling rate for layer after two additional layers are deposited ........................................................................68
A.20 TTT predicted single pass wall cooling rate for layer 11 and above after two additional layers are deposited ........................................................................69
A.21 TTT predicted cooling trends for all initially deposited layers .......................69
A.22 TTT predicted single pass wall cooling rate for all trend lines when an additional layer is deposited on existing substrate .................................................................70
A.23 TTT predicted single pass wall cooling rates for all trendlines when a second layer is deposited on existing substrate .................................................................70
B.1 CCT predicted single pass wall cooling rate for layer 1 ........................................71
B.2 CCT predicted single pass wall cooling rate for layer 2 ........................................72
B.3  CCT predicted single pass wall cooling rate for layer 3

B.4  CCT predicted single pass wall cooling rate for layer 4

B.5  CCT predicted single pass wall cooling rate for layer 5

B.6  CCT predicted single pass wall cooling rate for layer 6

B.7  CCT predicted single pass wall cooling rate for layer 7 and 8

B.8  CCT predicted single pass wall cooling rate for layer 9

B.9  CCT predicted single pass wall cooling rate for layer 10

B.10 CCT predicted single pass wall cooling rates for layers 11 and above

B.11 CCT predicted single pass wall cooling rate for layer 1 after two additional layers are deposited

B.12 CCT predicted single pass wall cooling rate for layer 2 after two additional layers are deposited

B.13 CCT predicted single pass wall cooling rate for layer 3 after two additional layers are deposited

B.14 CCT predicted single pass wall cooling rate for layer 4 after two additional layers are deposited

B.15 CCT predicted single pass wall cooling rate for layer 5 after two additional layers are deposited

B.16 CCT predicted single pass wall cooling rate for layer 6 after two additional layers are deposited

B.17 CCT predicted single pass wall cooling rate for layer 7 and 8 after two additional layers are deposited

B.18 CCT predicted single pass wall cooling rate for layer 9 after two additional layers are deposited
B.19  CCT predicted single pass wall cooling rate for layer 10 after two additional layers are deposited

B.20  CCT predicted single pass wall cooling rate for layer 11 and above after two additional layers are deposited

D.1  Stress vs Strain Results for the Build Direction Specimens

D.2  Tensile Data for the Build Direction Specimens

D.3  Stress vs. Strain Data for the Build Plane Specimens

D.4  Tensile Data for the Build Plane Specimens
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Chemical composition of 4340 alloy steel</td>
</tr>
<tr>
<td>2.2</td>
<td>Mechanical properties of wrought 4340 alloy steel</td>
</tr>
<tr>
<td>2.3</td>
<td>Expected hardness of four typical phases of steel</td>
</tr>
<tr>
<td>4.1</td>
<td>Vickers micro hardness data for the Z1-1 sample</td>
</tr>
<tr>
<td>4.2</td>
<td>Vickers micro hardness data for the Z1-5 sample</td>
</tr>
<tr>
<td>4.3</td>
<td>Build direction and build plain specimen tensile data</td>
</tr>
<tr>
<td>C.1</td>
<td>1/16” Hardness testing of Z1 sample</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

1.1 Introduction to Additive Manufacturing

Additive Manufacturing (AM), also referred to as 3D printing, is an ever-growing field of manufacturing in which material is added rather than subtracted to form a near net shaped part. As per ASTM designation F2792-12a, AM is defined as a “process of joining materials to make an object from a 3D model, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [1]. The various categories of AM processing are summarized in Figure 1.1 and are grouped by the starting stock material and the heat source used to deposit the material. As noted in the figure, the methods have tradeoffs between feature resolution and deposition rate. The starting feedstock in AM is typically powder or wire and the heat source can be either a laser, electron beam or arc. While laser powder bed fusion (L-PBF) builds are made in a layer-by-layer fashion within a powder bed, other processes such as blown powder deposit (L-BPD) or wire arc deposition (WAAM) can occur outside of a powder bed and are referred to as Direct Energy Deposition (DED) processes [2].
Figure 1.1 Deposition rate vs. resolution of various metal additive manufacturing processes [2].

The specimens used in this study were deposited using the WAAM equipment which is mounted on a gantry frame and is located in the Advanced Manufacturing Laboratory at UAH [3, 4]. Figure 1.2 illustrates the WAAM process in which wire feedstock is inserted into the path of an electric arc heat source. The melted wire is deposited as beads onto a substrate or previous layer according to the pathing defined from a sliced CAD file. As deposited material solidifies, the additional material is deposited in repeating layers until the build geometry is complete. While WAAM builds do not have the highest resolution of the various AM processes, they have the highest deposition rate [5].
1.2 Microstructure Formation in Additively Manufactured Parts

AM is a rapid solidification process in which the molten bead of material goes from liquid to solid in fractions of a second upon touching the substrate. Typical solidification cooling rates found in literature range from \(~120\) K/s at 2 to 3 seconds after deposition to \(~2\) K/s and fractions of K/s when nearing room temperature [7, 8, 9]. Components fabricated through AM processes generally have different microstructures and hence properties from those of their wrought or cast counterparts. This is due to the
complex thermal profile that develops during an AM build, in which the material is rapidly melted, solidified, and reheated repeatedly. Thus, understanding and ultimately predicting the resulting microstructure relies on the understanding the thermal profile as a function of the processing parameters including the deposition strategy.

The rapid solidification aspect of AM is similar to fusion welding processes, thus modeling efforts in that field have relevancy. Figure 1.3 illustrates a fusion weld bead which consists of three major zones: the fusion zone (FZ), which undergoes melting and solidification, the unmelted heat affected zone (HAZ) which is adjacent to the fusion zone and experiences solid-state phase changes but no melting, and the unaffected base metal [8,10]. The FZ has a direct effect on the resulting size and shape of grains, the extent of segregation, and the distribution of inclusion and defects [8]. In an AM part, the deposited molten material reacts similarly to the FZ. As the part is built, the previous layers and portions of the same layer not in the FZ are like the HAZ.

![Figure 1.3](image.png) Three major zones of a fusion weld [7].
The orientations used in an AM build are illustrated in Figure 1.4. During an AM build, the previously deposited solidified layers, in the Z direction, experience repeated heating and cooling during the deposition of successive layers [11]. The red lines represent the melt-in-areas between layers. Since, the heat source is traveling over the same coordinate location in the XY build plane, layer upon layer, the grain growth direction is largely dependent on the heat flow in the build direction (Z). Reported methodologies to reduce the temperature gradients and hot spots rely on pathing choices such as reversing direction from layer to layer in order to distribute heat more evenly [12]. Although the grain orientation in the XY build plane alters layer upon layer, the grains are reported to grow in the direction of heat flow (Z) resulting in columnar microstructures in the build direction in the as-built part [13]. This grain structure can result in anisotropic properties of the final build unless modified during post processing heat treatment.

Figure 1.4   WAAM AM build orientations showing the build plane (XY) and build direction (Z).
1.3 Thermal Predictions in Additive Manufacturing

Numerical transient thermal models applied to AM are typically based on the single-point heat source model [14] that starts with the formation of a melt pool. These models use a ground-up approach that builds off the melt pool characteristics as a function of the heat flux. This approach is usually localized to the area around the heat source, encompassing tracking of only one or two passes over the substrate. The substrate is usually held at a constant temperature to reduce variables. Complex physics-based models are also used which require finer mesh sizes that require more computational resources, such as super-computers [14]. To predict the global residual stresses and microstructural evolution based on the global thermal profile of a build requires larger length scale numerical models [15]. These approaches become computationally expensive when trying to scale to an actual AM build size.

To anchor transient thermal modeling predictions requires monitoring the temperature and its gradients during an AM process. These temperature gradients are difficult to measure accurately in-situ with typical temperature measuring devices. Thermocouples provide single-point readings and insertion of the thermocouple into a build can affect the resulting mechanical properties. Installation of thermocouples in the base plate can alleviate the concern for consumption during a build. Thermocouples will not be able to give the temperature at the deposited layer but rather the temperature at increasing distances [16] as the a AM build progresses. Thermal measurements using infrared cameras and infrared thermometers are difficult due to the saturation of the imaging device by the heat source. Thus, temperature data can only be obtained after the
heat source is turned off, often missing key information regarding the resulting temperature gradients. Therefore, the complex thermal processing cycles in AM require a deeper understanding of the relationship between processing, material properties, and microstructure [17].

In AM there are several variables that affect the thermal profile including: the energy density of the heat source, scanning strategy, and dwell time. If temperature gradients could be obtained during the build, non-equilibrium diagrams can be used to predict the resulting microstructure and hence properties of the resulting build. This would allow the transient thermal models to be anchored to improve their applicability.

Many modeling approaches have been taken as additive manufacturing has gained interest since its inception. The challenge of modeling is computational requirements. Patil, Pal, and Stucker [18] developed a finite element model utilizing multi-scale simulation with adaptive mesh refinement. While still being faster than some similar commercial products, it still requires excessive computational resources. Steuben, Birnbaum, Michopoulos, and Iliopoulos [19] created a thermal behavior model for metal printing processes at a lower computational cost for a select build geometry. However, it requires enrichment functions for factors involved in additive manufacturing for each geometry with compensation functions being necessary for some geometries. Many thermal models that have been or are being designed currently are either testing for function or being compared to measurable data readings from thermocouples or other similar devices.

The objective of this study is to use a top-down approach using a finite difference additive thermal model (DATM) created by Stockman [20] to predict thermal gradients in
an AM build of 4340. A nominal approach to evaluating the predicted cooling rates
determined by DATM using a microstructural analysis to metallurgically evaluate an as
built 4340 alloy steel AM part. By anchoring the predictions with resulting
microstructures, the effectiveness of this top down approach can be evaluated.
2.0 BACKGROUND INFORMATION

2.1 Overview of DATM

DATM is a mass added, numerical transient thermal model previously developed for AM with the goal of minimizing computational resources by use of simplifying assumptions [20]. DATM was programmed in open source Python 2.7 as a first order approach to predicting the global temperature profile throughout the entire part for the entire build [20, 21]. Simplifying assumptions about the complex physical phenomenon involved in an AM build were made to reduce the computational resources required. For instance, the model simplifies heat flux to a Cartesian mesh cuboid around the center of the molten pool and material properties for the build material are assumed constant. More information regarding the model development and assumptions can be found in the dissertation by Stockman [20].

DATM is based on a 3D finite difference scheme with the heat source input as an effective temperature controlled block [21]. This provides the advantage of predicting global temperature gradients depending on the flux of the heat source. The final part geometry is completely meshed, but nodes are only computationally activated as material
is added during the build. The meshing is based off the CAD file used to generate input to the AM process. User inputs define the meshing which is designed to be coarse using X and Y spacing equivalent to half the distance between neighboring passes, with Z spacing as the average layer height [20, 21] This gives a 50% overlap between passes or layer deposition. Conduction is the main route of heat transfer in this study which uses a nominal 20.32 cm wide x 20.32 cm tall (8” x 8”) build size. The model also has provision for convection and radiation, although they were found to not significantly contribute to the heat transfer for a build of this size. Convection is present in each layer but begins to account for greater heat transfer as the layer count increases eventually following a thin fin model [22]. Constant emissivity is assumed for radiation since it was not found to significantly affect the resulting temperature gradient within the temperature range of interest [20]. User selected points from the database generated are used to produce graphs and charts. By modeling the AM build in sections, the thermal data can be isolated for the various layers.

2.2 Material - Alloy Steel 4340

A low carbon steel was selected for this study as time-temperature-transformation (TTT) and continuous-cooling-transformation (CCT) diagrams are readily available for predicting the non-equilibrium microstructure evolution. Table 2.1 summarizes the elemental composition of AMS 6456E or 4340 alloy steel. Steel alloy 4340 is a medium carbon, heat treatable, high strength low alloy (HSLA) steel used for critical structural
applications due to its toughness, tensile strength and retention of fatigue strength at elevated temperatures. The material finds most of its uses in structural applications such as aircraft landing gear, engine pistons, gears and bearings, and firearm components. Carbon (C) additions, up to 2 wt%, control the phase formation in iron (Fe) based steels and hence strength. Nickel (Ni) is the primary alloying element which forms a solid solution with the Fe without the formation of carbide compounds [23].

Table 2.1 Chemical composition of 4340 alloy steel.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wrought Material Content (wt%) [23]</th>
<th>Vendor supplied wire Content (wt%) [24]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron, Fe</td>
<td>95.20 – 96.33</td>
<td>1.83</td>
</tr>
<tr>
<td>Nickel, Ni</td>
<td>1.65 – 2.00</td>
<td></td>
</tr>
<tr>
<td>Chromium, Cr</td>
<td>0.700 – 0.900</td>
<td>0.80</td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.600 – 0.800</td>
<td>0.80</td>
</tr>
<tr>
<td>Carbon, C</td>
<td>0.370 – 0.430</td>
<td>0.35</td>
</tr>
<tr>
<td>Molybdenum, Mo</td>
<td>0.200 – 0.300</td>
<td>0.25</td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>0.150 – 0.300</td>
<td>0.24</td>
</tr>
<tr>
<td>Sulfur, S</td>
<td>0.0400</td>
<td>0.002</td>
</tr>
<tr>
<td>Phosphorous, P</td>
<td>0.0350</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Copper, Cu</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Hydrogen, H</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Nitrogen, N</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Oxygen, O</td>
<td>0.0016</td>
<td></td>
</tr>
</tbody>
</table>

The elemental composition of the 4340 alloy steel wire received for study was within the specifications for wrought material. The copper (Cu), hydrogen (H), nitrogen
(N), and oxygen (O) are not intentional alloying elements but are either inherent in the base material or else result from contamination during the wire drawing process.

Table 2.2 summarizes the expected mechanical properties for wrought 4340 steel.

Table 2.2 Mechanical properties of wrought 4340 alloy steel [23].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>745 MPa</td>
<td>108 ksi</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>470 MPa</td>
<td>68 ksi</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>190-210 GPa</td>
<td>27,557-30,458 ksi</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td>Hardness, Brinell</td>
<td>217</td>
<td>217</td>
</tr>
<tr>
<td>Hardness, Rockwell B</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Hardness, Rockwell C</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

2.3 Equilibrium Phases in 4340 Alloy Steel

A Fe-C phase diagram in Figure 2.1 summarizes the equilibrium microstructures for steel based on C content. Steels move from a liquid phase to the austenitic phase. From austenite, steel can cool to form three equilibrium phases of steel at room temperature. Those included are ferrite, cementite, and pearlite. Pearlite, which is a mixture of ferrite and cementite, is considered a phase of its own. The physical properties of steel include melting point, density and thermal conductivity, which are not significantly affected by alloying. The heat treatment affects the final microstructure and
the resulting mechanical properties. The austenite, or $\gamma$-Fe, is the high-temperature phase in steel. At these temperatures, the C goes into solid solution in the face centered cubic (FCC) lattice structure. Up to 2% C is soluble in the $\gamma$-Fe, defining the subcategory of steel [25, 26, 27]. All heat treatments for steel start within the single-phase $\gamma$-Fe region as its decomposition controls the final non-equilibrium phase transformations. Thus, heat treatments raise the steel above a critical temperature ($A_1$, $A_3$, or $A_{cm}$), which varies slightly depending on the alloying elements. Materials with an FCC structure, such as $\gamma$-Fe, are not magnetic.

Ferrite, also referred to as $\alpha$-Fe, is essentially pure Fe with a body-centered cubic (BCC) lattice structure [27, 28]. As summarized in Table 2.3, ferrite is the softest and least hardenable of the phases and magnetic. When conducting heat treatments from the $\gamma$-Fe region, grain boundary ferrite is the first phase to form under equilibrium, slow cooling conditions [24].

Pearlite is comprised of lamellas of cementite (Fe$_3$C) and ferrite that derives its name from the mother of pearl appearance in polished samples [27]. The cementite has an orthorhombic lattice structure containing 6.7% C, which is extremely hard and brittle [27, 28]. At the eutectoid composition of 0.83% C, all austenite transforms into the thermally equilibrium phase of pearlite. The hardness of pearlite is inversely proportional to the layer thickness, which depends on the cooling rates. Table 3 compares the expected hardness for the four typical room temperature phases found in steel, both equilibrium and non-equilibrium.
Table 2.3  Expected hardness of four typical phases of steel [25, 29].

<table>
<thead>
<tr>
<th>Phases</th>
<th>Rockwell</th>
<th>Vickers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martensite</td>
<td>49-66 HRC</td>
<td>497-890</td>
</tr>
<tr>
<td>Bainite</td>
<td>24-49 HRC</td>
<td>252-497</td>
</tr>
<tr>
<td>Pearlite</td>
<td>100 HRB</td>
<td>252</td>
</tr>
<tr>
<td>Ferrite</td>
<td>47 HRB</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2.1  Fe-C equilibrium phase diagram [25].
2.4 Non-equilibrium Transformations Diagrams for 4340

The phase diagram, shown in Figure 2.1, contains only the equilibrium phases of steel as a function of C content and does not consider the effect of the cooling rate on the kinetics of the transformations. In order to cover the non-equilibrium phases, an isothermal time-temperature-transformation (TTT) diagram is used as shown in Figure 2.2. The TTT diagram for steels begins with the temperature of the austenitic region and describes isothermal cooling. The TTT diagram includes two additional non-equilibrium phases of martensite and bainite that form during more rapid cooling.

![Diagram](image)

Figure 2.2   Time-Temperature-Transformation diagram for 4340 alloy steel [30].
Bainite forms by a lamellar combination of cementite and ferrite, like pearlite but with finer spacing. The resulting microstructure has very finely spaced lamellae and can take on a plate-like structure. The strengthening mechanism comes from the lattice mismatch between the two phases and relies on interfacial strengthening [25, 30]. Its hardness lies between that of pearlite and martensite.

Martensite has a body centered tetragonal (BCT) lattice structure that is highly stressed and super saturated with C [25, 27]. It is the strongest and hardest phase of steel but also the least ductile. The microstructure that develops during martensitic transformation is driven by the need to minimize internal energy [25, 31]. During very rapid cooling, or quenching, from the austenite phase, the C atoms become trapped as the FCC phase becomes unstable, trapping the supersaturated C atoms resulting in a strain induced transform to BCT. This austenite-to-martensite transformation is strain induced and doesn’t require diffusion [25, 29, 32]. Martensite microstructures include both lath-like and plate-like structures. To reduce the hardness and promote some ductility, a tempering heat treatment process decomposes portions of the martensite where the super saturated carbon transforms into graphite or cementite.

As not all heat treatments are conducted isothermally, the continuous cooling transformation diagram (CCT) provides information on the variation of phases due to unequal cooling rates between the surface and center of a part. Figure 2.3 is an example of a CCT diagram for 4340. This tool maybe more useful in evaluating the resultant microstructure in AM due to the reheating nature that occurs during a build.
Figure 2.3  Continuous-Cooling-Transformation diagram for 4340 [28].
3.0 EXPERIMENTAL PROCEDURE

3.1 Build Plan for Single Pass Wall

Figure 3.1A illustrates the single pass, single bead wide, 4340 plate built using WAAM (nominal dimensions of 20.5 cm x 20.5 cm and 0.65 cm thick). The build was positioned 2” from center on a 25.4 x 25.4 cm (10” x 10”) build plate of 0.97 cm (0.38”) thickness. Figure 3.1B provides information on the pathing for each layer, showing a reversed direction between layers. The green line indicates the layer thickness and the red line shows the deposition direction for each layer. A 60 s dwell time was implemented between each layer. The build continued until the desired height was achieved with no other stoppages other than the dwell time.
Figure 3.1  Single-pass wall build plan (A) and pathing directions (B).

### 3.2 Cut Plan for Test Specimens

After deposition, the plate was cut into subscale tensile bars as shown in Figure 3.2. The cut plan layout is shown in Figure 3.3. The cut plan was designed to give an appropriate number of tensile specimens for both the build direction (X-Y plane vertical) and build plane (Z horizontal) to evaluate possible anisotropy. The cut plan was also designed to take an equal number of specimens from the lower half and upper half of the build in addition to opposite sides of the plate for both orientations as well. For three of
the vertical specimens, the build plate was included in the cut plan so the transition at the interface could also be evaluated.

Figure 3.2  Tensile specimen dimensions in inches.
DATM was used to predict the temperature gradients developing during the manufacturing process according to the pathing instructions used. The results of this model were used to predict the expected phases present in the 4340 alloy steel build as a function of the build height. Since the austenitic region is nominally at ~723 °C, any temperature increases below this threshold will not quickly affect current microstructure. This implies that when the heat of additional layers deposited does not cause previously
deposited layers to go above this threshold, it is not expected to result in different microstructural evolution on a layer by layer basis but only a coarsening of previously formed phases.

Based on the available literature for melt pool temperatures in fusion welding, the predictions assumed 1627 °C (1900 K) as the initial temperature of the melt pool. This includes a 200 °C (200 K) increase over the reported 1427 °C (1700 K) melting temperature [33, 34] for 4340 alloy steel to allow for superheating. The temperature gradient of the first layer will always be the highest as it is the only layer which begins at 27 °C (300 K) room temperature. At some point in the Z direction of the build, the temperature of subsequent layers will follow the same temperature gradient profile of the previous layer. This is a prediction due to the heat transfer effects hitting a consistent pattern of heat flow in each layer and cooling trends will stay the same beyond this point in DATM. The steps chosen for the single-pass build began with 50 °C increments from 300 °C to 500 °C and then decreased to 25 °C steps until 625 °C is reached, as 625 °C is predicted to be the highest substrate temperature as predicted by DATM.

As the model is run, a database of temperature versus time is generated. Incremental points of interest are isolated from the database to predict cooling rates relative to the localized build plane versus the global build. To obtain the localized cooling rate, the relative temperature of deposited substrate to the next two subsequent layers deposited is evaluated. In grouping of these top three layers, this predicted cooling rate is overlaid on TTT and CCT diagrams for comparison with the metallography. To obtain the global temperature gradient, the substrate temperature is tracked during the build as additional layers are added. This allows the effect of
subsequent reheating on the build to be evaluated. By using both the TTT and CCT diagrams, a better understanding of the non-equilibrium heating effects can be evaluated.

3.4 Experimental Procedure

Each individual experiment aside from modeling was divided into its own section for ease of understanding. Hardness testing, mechanical property testing, optical microscopy, and scanning electron microscopy were completed for this study.

3.4.1 Hardness Testing

Hardness profiles along the build direction (Z) were obtained to show a hardness profile of the plate with respect to build height. All measurements were taken from the Z1 specimen. Figure 11 illustrates the Z1 sample being segmented into five smaller samples, Z1-1 to Z1-5, with the height of each sample in mm. Measurements were made using a Wilson Hardness Tester on the Rockwell B scale using a 1/16” ball indenter. Prior to conducting the indents, a calibration block was used to verify the machine readings.

Vickers hardness profiles along 2 samples from the Z1 specimen in Figure 3.4 for sections Z1-1 and Z1-5, were completed using a Micro Vickers Hardness Tester Tukon 2100. This was done to correlate the data between regions of fine grains and coarse
grains in the samples to better understand the hardness profile. Prior to conducting the indents, a calibration block was used to verify the machine readings.

Figure 3.4 Specimen breakdown of the Z1 sample.

3.4.2 Mechanical Properties

Mechanical properties were determined using quasi-static tensile tests. An Instron 5985 load frame with a 250 kN load cell was used in displacement control. A constant crosshead velocity of 1.27 mm/min (0.05 in/min) was used in accordance with ASTM E8 [35]. The subscale specimen geometry was not in compliance with the
standard. The size of the as-built wall did not allow for an equal number of specimens in both orientations following the standard. The gauge length of the specimens used were nominally 22.9 mm instead of the 25 mm ± 0.1. Overall length was 76.2 mm, short of the standard length of 100 mm. Length of the reduced parallel section and grip section length was short of standard measure as well. Grip section width was larger than the standard 10 mm and was ~20.3 mm. This was done due to issues with WAAM specimens having defects in the build or defects originating from machining and the rough surface finish that is present in as-built parts. Specimen thickness, central width, and radius of fillet followed standard protocol.

3.4.3 Optical Microscopy

Sample Z1 from the single pass build was used for optical microscopy. Standard metallographic grinding and polishing procedures were followed with a final polish of 0.05 μm colloidal silica. To examine the resulting grain structure, the samples were etched using Nital for 10 seconds. Optical images were captured using a Zeiss XioVert.A1m Inverted Microscope for Reflected Light Techniques. Approximately 10 bright field images were taken of random locations on each sample in order to calculate the volume fractions of the phases present.
3.4.4 Scanning Electron Microscopy

The Z1 sample was also imaged using scanning electron microscopy (SEM) for higher magnification. The samples were repolished for imaging to remove the etchant. Standard metallographic grinding and polishing procedures were followed with a final polish of 0.05 µm colloidal silica. Images were captured using a Hitachi SU5000 Scanning Electron Microscope.
4.0 EXPERIMENTAL DATA

4.1 DATM Model Predictions of Temperature Gradients for an Example Build

Overlaid curves are obtained from DATM predictions from the start of an example projected build until the end of the build as shown in Figure 4.1. The orange line, showing smooth data, predicts that this layer will reach and maintain temperatures of 227 °C (500 K) for around 1000 s and 127 °C (400 K) for almost 5000 s. As this holds the layer at elevated temperatures, the predictions indicate a possible tempering effect or in-situ heat treat is possible.

These curves are then overlaid on either TTT or CCT diagram to consider what phases would be expected in the example under conventional heat treatments. The TTT diagram in Figure 4.2 shows the predicted rate of cooling would only cross the bainite region. While not an isothermal hold, it is a quick reference to show that the bainite phase transformation should occur within the predicted cooling time. For the WAAM printing of 4340, the cooling rates are not high enough to expect the formation of martensite.

In the CCT diagram in Figure 4.3, under continuous cooling conditions, the red line indicates that some pearlite may form before the majority transformation to bainite.
Again, the cooling rates are not predicted to be not high enough for the formation of martensite.

Figure 4.1 DATM projection of cooling for initial layer with room temperature substrate.
Figure 4.2  Cooling predictions for a bainite curve example with a TTT diagram for 4340 [30].
Figure 4.3  Cooling predictions for a bainite curve example with a CCT diagram for 4340 [28].

4.2 DATM Model Predictions of Temperature Gradients

All temperature gradients for the 4340 WAAM build cooled from the 1627 °C (1900 K) melting temperature to between 27 °C (300 K) and 352 °C (625 K). The predictions following are for cooling trends overlaid on the 4340 CCT diagram as shown previously in Figure 4.3. Layer 1 of Figure 4.4 is the only layer that can start at a 27 °C
substrate temperature, the initial temperature of the build plate. It follows a cooling rate of 21.3 °C/s. Layers 2, 3, 4, 5, and 6 follow the trend lines of 17.8 °C/s, 16.1 °C/s, 10.7 °C/s, 10 °C/s, and 9.1 °C/s substrate temperature, respectively. Layers 7 and 8 follow the temperature gradient line of 7.5 °C/s. Layers 9 and 10 follow the temperature gradient trend lines of 6.1 °C/s and 5.1 °C/s, respectively. Layers 11 and through the rest of the build follow the 4.1 °C/s substrate temperature line.

The trendlines are displayed in Figure 4.4 include the cooling rates of all trends for the entire build. DATM predicts the formation of martensite in layers 1, 2, and 3 as they cool without passing through any other transformations. Layer 4 is predicted to pass through the martensitic region at the highest temperature of the layers and should contain some martensite mixed with bainite. All other layers are predicted to contain a mixture of proeutectoid ferrite, pearlite and bainite. No layers complete a full transition through any phase and will contain mixed phases. This correlates with those found in the TTT diagrams located in Appendix A and individual CCT diagrams located in Appendix B.
Figure 4.4  CCT predicted cooling rates when layers are initially deposited [28].
The predictions for an additional layer being deposited, Figure 4.5, indicate that very few layers even reach a partial phase change as they are not able to cool long enough before the heat source returns. Only layers four, five, and six are predicted to have a partial phase change to bainite. As mentioned for the initial layers, all other layers are predicted to contain a mixture of proeutectoid ferrite, pearlite and bainite.
When a second additional layer is deposited onto the previous substrate, Figure 4.6, layers one and two do not begin at the needed temperature to reach the austenitic region and therefore are omitted. Layers three through nine will partially phase change to bainite, while layers ten and beyond do not reach a phase change curve and therefore will not be able to be predicted. All layers will contain pearlite and ferrite as before.
The final predictions by layer were made using these CCT diagrams in conjunction with the DATM cooling trends for the entire build. The overlay of the tempering heat curve that each initial layer undergoes through the build was shown in Figure 4.7 for determining the previous predictions of martensite in the final microstructure that were generated from the CCT diagrams.

![CCT Diagram](image.png)

Figure 4.7 DATM tempering predictions for the entire build [30].
As it can be seen in Figure 4.7, martensite is not predicted to be a possible phase due to the tempering effects that occur as heat is transferred throughout a wall build. Bainite was predicted for possible phase formation in layers 1 through 6. Layers 1 through 3 fully cross the bainite transformation lines, while 4 through 6 will contain only partial transformations. Layer 7 and 8 enter the higher end of the bainite curve but just barely. Most likely indicating that if it is there, it will be only a very small portion. Layers 9 and above do not enter the transformation curves and therefore will not contain any phases besides pearlite and ferrite. Pearlite and ferrite will also be present in all layers of varying percentages dependent on the amount of bainite present.

4.3 Hardness Data

The expected hardness of 4340 in the fully annealed condition is 95 HRB [23]. Tables 4.1 and 4.2 display the data from the Vickers micro hardness test conducted on the Z1-1 and Z1-5 samples along with corresponding HRB values. 1/16” indenter hardness data is located in Appendix C.
Table 4.1  Vickers micro hardness data for the Z1-1 sample.

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Layer</th>
<th>HRB</th>
<th>Vickers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>Layer 4 &amp; 5 interface</td>
<td>107</td>
<td>322</td>
</tr>
<tr>
<td>Fine</td>
<td>Layer 4</td>
<td>109</td>
<td>354</td>
</tr>
<tr>
<td>Fine</td>
<td>Layer 3</td>
<td>110</td>
<td>362</td>
</tr>
<tr>
<td>Coarse</td>
<td>Layer 2 &amp; 3 interface</td>
<td>107</td>
<td>327</td>
</tr>
<tr>
<td>Fine</td>
<td>Layer 2</td>
<td>108</td>
<td>333</td>
</tr>
<tr>
<td>Coarse</td>
<td>Layer 1 &amp; 2 interface</td>
<td>107</td>
<td>315</td>
</tr>
</tbody>
</table>

Table 4.2  Vickers micro hardness data for the Z1-5 sample.

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Layer</th>
<th>HRB</th>
<th>Vickers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>Layer 5 &amp; 6 interface</td>
<td>109</td>
<td>354</td>
</tr>
<tr>
<td>Coarse</td>
<td>Layer 4 &amp; 5 interface</td>
<td>109</td>
<td>351</td>
</tr>
<tr>
<td>Fine</td>
<td>Layer 4</td>
<td>107</td>
<td>320</td>
</tr>
<tr>
<td>Coarse</td>
<td>Layer 3 &amp; 4 interface</td>
<td>109</td>
<td>356</td>
</tr>
<tr>
<td>Coarse</td>
<td>Layer 2 &amp; 3 interface</td>
<td>108</td>
<td>338</td>
</tr>
<tr>
<td>Fine</td>
<td>Layer 1</td>
<td>106</td>
<td>309</td>
</tr>
</tbody>
</table>
4.4 Mechanical Properties

The reduced mechanical properties are summarized in Table 4.3 for the build direction and build plane samples. The H specimens (build plane or horizontal) were found to have higher ultimate tensile strength and elongation that the Z specimens (build direction or z direction) when looking at average results for each category. The Z samples had a more consistent yield strength than the H samples. The chart displays of this data can be found in Appendix D.

Table 4.3 Build direction and build plain specimen tensile data.

<table>
<thead>
<tr>
<th></th>
<th>Yield (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z2</td>
<td>242</td>
<td>730</td>
<td>13.6</td>
</tr>
<tr>
<td>Z3</td>
<td>243</td>
<td>695</td>
<td>12.9</td>
</tr>
<tr>
<td>Z4</td>
<td>312</td>
<td>605</td>
<td>9.0</td>
</tr>
<tr>
<td>Z5</td>
<td>256</td>
<td>520</td>
<td>8.2</td>
</tr>
<tr>
<td>Z6</td>
<td>242</td>
<td>685</td>
<td>21.8</td>
</tr>
<tr>
<td>H2</td>
<td>130</td>
<td>460</td>
<td>6.1</td>
</tr>
<tr>
<td>H3</td>
<td>317</td>
<td>740</td>
<td>19.2</td>
</tr>
<tr>
<td>H4</td>
<td>267</td>
<td>700</td>
<td>18.6</td>
</tr>
<tr>
<td>H5</td>
<td>196</td>
<td>725</td>
<td>20.6</td>
</tr>
<tr>
<td>H6</td>
<td>207</td>
<td>680</td>
<td>22.5</td>
</tr>
<tr>
<td>AVG Z</td>
<td>259 ± 27.0</td>
<td>647 ± 76.1</td>
<td>13.1 ± 4.9</td>
</tr>
<tr>
<td>AVG H</td>
<td>223 ± 47.0</td>
<td>660 ± 80.0</td>
<td>17.3 ± 2.9</td>
</tr>
<tr>
<td>Wrought [21]</td>
<td>470</td>
<td>745</td>
<td>22</td>
</tr>
</tbody>
</table>
4.5 Microstructure Analysis

The microstructural analysis findings have been broken down into optical microscopy and scanning electron microscopy.

4.5.1 Optical Microscopy

Sample Z1 was divided into 5 roughly equivalent segments as shown in Figure 3.4. After metallurgical preparation, multiple images were taken of each segment to form a montage. Figures 4.8 - 4.12 show representative stitched images from the base plate through the top of the Z1 sample to evaluate any microstructure changes.
Sample Z1-1, shown in Figure 4.8, covers the first 5 layers from the build plate and shows bands of very fine grains separating bands of larger grains. The brownish/orange coloration located at the bottom of Z1-1 is the base plate. Banding of fine and coarse grains is evident throughout the entire build. Larger, coarser grains are located centrally to each independent layer’s melt pool where heat resides for the longest amount of time. The finer grains are located at the edges of overlaps between layers, where a new layer is deposited onto a previous layer. These regions cool at a faster rate leading to finer grains. Grains are seen to be growing in the Z direction as the build is taking place. This is due to the heat source oscillating back and forth as the build progresses. Grains will grow in the direction of the heat source, and this more vertical distribution of grains is typical of WAAM builds.

The fine grains seen in the Z1-1 sample are too fine to determine the phase makeup with optical microscopy, but the coarser grains are ferrite, lighter colored areas, among areas of pearlite, which appear as a mixture of lighter, ferrite, and darker, Fe₃C. Also, a wave type pattern is present on the entire sample. This is most likely an effect from etching or imaging. The superficial wave pattern is not representative of the layers themselves but is present in all samples used. Vickers hardness test dimples are present in this sample in the upper half, but some inclusions and/or voids are present as well.
Figure 4.8  The Z1-1 sample ranging from the baseplate to layer 5 in the Z direction.
Sample Z1-2 image are shown in Figure 4.9, including layers 6 - 10. The grain structure is very similar to the Z1-1 specimen. Optical microscopy is not able to define which phase makes up the finer grains. Larger grains are areas of pearlite and ferrite as discussed for the Z1-1 sample. Grains continue to grow vertically as before. The only difference is the transition areas from coarse to fine grain regions are not as distinct throughout in this specimen. This could be due to heat buildup in the part causing the fine grain regions to be coarser than what is seen in the fine grain regions of earlier layers. The coarse grain regions are also larger in this sample than those found in the Z1-1 sample.
Figure 4.9   The Z1-2 sample going from layers 6 - 10 in the Z direction.
Figure 4.10 is representative of the next 5 layers in the build (11-15). Again, very similar results to the previous two. The coarser grain section makes up the individual layers and is a combination of pearlite and ferrite. The finer grained regions are not discernable with optical as mentioned before. This sample is more like Z1-2 than Z1-1 with larger coarse grain regions that easy to distinguish. Grains continue to grow in the Z direction and nothing else of note is taking place in this sample. A Vickers hardness test indention is in the lower portion of the image, but no visible inclusions are present.
Figure 4.10  The Z1-3 sample moving from layers 11 - 15 in the Z direction.
Figure 4.11 continues to move up the Z direction of the build showing layers 16-20. This sample is very similar to the Z1-3 sample. The same grain growth, size, and separation continues to occur as the build progresses. Vickers hardness indentions and some inclusions are present in the upper area of the sample.
Figure 4.11  The Z1-4 sample from layers 16 - 20 in the Z direction.
Figure 4.12, layers 21-28, shows the Z1-5 specimen, which is the upper portion of the Z1 sample. It is very similar to the previous two samples, Z1-3 and Z1-4. Vickers hardness indentions are located up the sample. Again, coarse grain regions made up of pearlite and ferrite, and the fine grain regions are indecipherable with optical microscopy.
Figure 4.12  The Z1-5 sample from layers 21 - 28 in the Z direction.
4.5.2 Scanning Electron Microscopy

SEM imaging were obtained for the bottom and top of the Z1-1 and Z1-5 samples. Figure 4.13, A-E, corresponds to the Z1-1 sample and figures 4.14, A-E, corresponds to the Z1-5 sample.

Figure 4.13  SEM images of the lower, middle, and upper locations in the Z1-1 sample.
Figure 4.13 (continued)

Figure 4.13 A-D are images of the bottom and middle of the Z1-1 sample. They all include a good representation of lathe bainite [36] indicating that the first 2 - 4 layers contain bainite. Figure 4.13 image E at the top of the Z1-1 sample, layers 4 - 5, does not contain bainite but does show pearlite. This does not indicate that bainite is not present, just that it was not captured in the chosen location of SEM.

Figure 4.14 A is located on a layer separation. This is indicated by the dendrite formations sharp change of direction, which is indicative of heat source in one layer traveling in an opposing direction in the next. Figure 4.14 B is a larger magnification and just off the layer separation line. It displays larger grains that appear to be dendrite growth. Figure 4.14 C, D, and E all contain pearlite and are like Figure 4.13 E with coarser grain sizes. The lamellar structure seen in typical pearlite images is not seen due to lower magnification of the images.
Figure 4.14  SEM images of the middle and upper locations of the Z1-5 sample.
5.0 DISCUSSION

All data obtained has confirmed the predictions made using DATM and some other items of note. The multiple hardness tests indicate that the as-built 4340 is harder than wrought 4340. This can be due to either harder phases being present or to a heat treatment effect. Both would increase the hardness over wrought material. These results are noteworthy, but the other results must be used in addition to this to finalize a conclusion.

The tensile test data shown in Tables 4.3 confirms what has been found in experimentation and literature about WAAM, which is that the tensile specimens are weaker than wrought. The deformations that can exist in WAAM, whether voids or inclusions, will yield lower results in mechanical properties. The horizontal build plane samples overall were stronger and had greater elongation than the vertical build direction samples. The horizontal samples are made of fewer layers but are longer bands of welded material, whereas the vertical samples are many layers of welded material stacked upon one another. This explains the results because any layer that has voids or unwanted inclusions would yield at a lower value. There are more layers for this to occur in the vertical specimens leading to lower yield strength in the as built samples.

The microscopic analysis is what is necessary to prove or disprove the model
predictions. The model predictions were able to capture cooling rates that occurred in the as built wall. The predictions called for martensite to be in the first 3 layers based off the CCT overlays only. However, when the temperature data from the entire build is looked at as a whole, the underlying reheating effect that occurs in the base plate and already deposited layers gives a different prediction. This tempering effect heated the lower layers up to the austenitic region or the temperature needed for a long enough period of time to break down the martensite that may have been located in those layers. The result of this is the final transformation to bainite in the first 3 to 4 layers. Layers 5 and 6 were predicted to have partially transformations to bainite. However, none was found during SEM. Two explanations exist for this. The first is simply that it was missed, because only partial transformations to bainite were predicted for these layers. How much of a partial transformation occurred is not something looked at in this study as only final resultant microstructure predictions with DATM were explored. SEM imaging takes time and more time could have been used to cover the entire sample in order to search for it. However, that does not mean that it would have been found in the scanning locations. This leads to the second explanation for it not being in those layers which is directly related to how much of a partial transformation occurred. Based off the predictions of subsequent layers from the CCT diagram, a partial transformation starts but only for about a minute or so before the next layer is deposited reheating and reorienting the previous microstructure. So, when the underlying tempering occurs in those layers, the partial transformations that were there may have been removed completely or broken down into such a small amount that it may be very difficult to find.
The model also predicted a point in the build, layer 11, where the cooling rate would follow a consistent pattern or reached quasi-static equilibrium in the cooling rate. Based, on the optical images, this was also confirmed as the Z1-3, Z1-4, and Z1-5 samples all look very similar and have similarly sized regions of coarse grains and fine grains. This follows logical train of thought, because if the cooling rates are very consistent, then the microstructure should also be very consistent.
6.0 SUMMARY

The lower in the build or closer a deposited layer begins to the build plate in an additive build, the steeper the cooling trend. This can drastically affect the end resultant microstructure of an as built AM part. An as-built WAAM part will contain heterogeneous microstructure throughout. The first layer will always have the steepest cooling curve unless parameters dictate the same interpass temperature before a layer begins. The resultant microstructure of an AM single-pass wall will eventually reach a point where every layer beyond will be very similar if not the same with no changes to build parameters or the build environment. The study found that the best results for phases that are determined by cooling rates will be located closest to the base plate in an as-built part.

Mechanical testing was not able to produce any item of note to help discern metallurgical differences through the part. Hardness data was able to show that the as-built part was harder than wrought and indicated that a phase that was stronger than pearlite may be present in the build. However, the data gathered from these tests was not able to help indicate final microstructure in the part.

The nominal approach to verifying model predictions outlined in this study has shown that cooling rate data for entire build needs to be considered for the best accuracy.
The cooling rates and temperature changes occur at faster rates and vary more over time than in traditional metal work. Lower layers will have higher cooling rates than layers occurring further along in the build. Also, when the heat source travels over a previous layer, much if not all the previous microstructure will be affected. A point in the build will reveal itself where a quasi-static cooling rate exists where each additional deposited layer will have a similar if not the same cooling rate. Additionally, as heat is drawn from the part to the base plate, previously deposited layers undergo an in-situ reheating or heat treatment type effect that alters previously formed microstructure again. Therefore, a multifaceted approach for predicting microstructure must be used. This study was able to prove that DATM can determine: the initial cooling rate of each layer, the affect additional deposited layers have on previously deposited layers, the layer at which a quasi-static equilibrium cooling rate is found, and the underlying reheating effect that takes place in a WAAM build in-situ.

The premise of this study worked as intended as the predictions made using the data from DATM yielded accurate metallurgical predictions when used in conjunction with CCT and TTT diagrams. Bainite was predicted in the lower layers of the build and with the use of optical and scanning electron microscopy it was found where predicted. Therefore, DATM’s predictions were verified. Also, the quasi-static cooling rate predicted by DATM was found to be accurate from metallurgical study. Layer 11 and above all followed a pattern of consistent microstructure which matched the consistent cooling rate. This nominal approach developed for this study may be a new avenue to be investigated further for its use in as-built additively manufactured parts.
APPENDICES
APPENDIX A

TTT Diagrams of DATM Predictions

Figure A.1  TTT predicted single pass wall cooling rate for layer 1 [30].
Figure A.2  TTT predicted single pass wall cooling rate for layer 2 [30].

Figure A.3  TTT predicted single pass wall cooling rate for layer 3 [30].
Figure A.4  TTT predicted single pass wall cooling rate for layer 4 [30].

Figure A.5  TTT predicted single pass wall cooling rate for layer 5 [30].
Figure A.6  TTT predicted single pass wall cooling rate for layer 6 [30].

Figure A.7  TTT predicted single pass wall cooling rate for layer 7 and 8 [30].
Figure A.8  TTT predicted single pass wall cooling rate for layer 9 [30].

Figure A.9  TTT predicted single pass wall cooling rate for layer 10 [30].
Figure A.10  TTT predicted single pass wall cooling rates for layers 11 and above [30].

Figure A.11  TTT predicted single pass wall cooling rate for layer 1 after two additional layers are deposited [30].
Figure A.12  TTT predicted single pass wall cooling rate for layer 2 after two additional layers are deposited [30].

Figure A.13  TTT predicted single pass wall cooling rate for layer 3 after two additional layers are deposited [30].
Figure A.14  TTT predicted single pass wall cooling rate for layer 4 after two additional layers are deposited [30].

Figure A.15  TTT predicted single pass wall cooling rate for layer 5 after two additional layers are deposited [30].
Figure A.16  TTT predicted single pass wall cooling rate for layer 6 after two additional layers are deposited [30].

Figure A.17  TTT predicted single pass wall cooling rate for layer 7 and 8 after two additional layers are deposited [30].
Figure A.18  TTT predicted single pass wall cooling rate for layer after two additional layers are deposited [30].

Figure A.19  TTT predicted single pass wall cooling rate for layer after two additional layers are deposited [30].
Figure A.20  TTT predicted single pass wall cooling rate for layer 11 and above after two additional layers are deposited [30].

Figure A.21  TTT predicted cooling trends for all initially deposited layers [30].
Figure A.22  TTT predicted single pass wall cooling rate for all trend lines when an additional layer is deposited on existing substrate [30].

Figure A.23  TTT predicted single pass wall cooling rates for all trendlines when a second layer is deposited on existing substrate [30].
APPENDIX B

CCT Diagrams of DATM Predictions

Figure B.1  CCT predicted single pass wall cooling rate for layer 1 [28].
Figure B.2  CCT predicted single pass wall cooling rate for layer 2 [28].
Figure B.3  CCT predicted single pass wall cooling rate for layer 3 [28].
Figure B.4  CCT predicted single pass wall cooling rate for layer 4 [28].
Figure B.5  CCT predicted single pass wall cooling rate for layer 5 [28].
Figure B.6  CCT predicted single pass wall cooling rate for layer 6 [28].
Figure B.7  CCT predicted single pass wall cooling rate for layer 7 and 8 [28].
Figure B.8  CCT predicted single pass wall cooling rate for layer 9 [28].
Figure B.9  CCT predicted single pass wall cooling rate for layer 10 [28].
Figure B.10  CCT predicted single pass wall cooling rates for layers 11 and above [28].
Figure B.11  CCT predicted single pass wall cooling rate for layer 1 after two additional layers are deposited [28].
Figure B.12  CCT predicted single pass wall cooling rate for layer 2 after two additional layers are deposited [28].

2nd layer

12.3 °C/s
Figure B.13  CCT predicted single pass wall cooling rate for layer 3 after two additional layers are deposited [28].
Figure B.14  CCT predicted single pass wall cooling rate for layer 4 after two additional layers are deposited [28].
Figure B.15  CCT predicted single pass wall cooling rate for layer 5 after two additional layers are deposited [28].
Figure B.16  CCT predicted single pass wall cooling rate for layer 6 after two additional layers are deposited [28].
Figure B.17  CCT predicted single pass wall cooling rate for layer 7 and 8 after two additional layers are deposited [28].
Figure B.18  CCT predicted single pass wall cooling rate for layer 9 after two additional layers are deposited [28].
Figure B.19  CCT predicted single pass wall cooling rate for layer 10 after two additional layers are deposited [28].
Figure B.20  CCT predicted single pass wall cooling rate for layer 11 and above after two additional layers are deposited [28].
APPENDIX C

Hardness Data for the Z1 Specimen

Table C.1  1/16” Hardness testing of Z1 sample.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Average Hardness in HRB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Sample</td>
<td>103.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>102.2 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>104.7 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>99.0 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>97.9 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>100.0 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>96.9 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>101.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>101.4 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>98.5 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>97.9 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>97.2 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>98.4 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>99.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>101.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>99.0 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>102.2 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>99.5 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>100.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>102.0 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>101.1 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>103.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>101.2 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>103.7 ± 0.7</td>
</tr>
<tr>
<td>Base Plate</td>
<td>101.6 ± 0.7</td>
</tr>
</tbody>
</table>
APPENDIX D

Mechanical Testing Data

Figure D.1  Stress vs Strain Results for the Build Direction Specimens.
Figure D.2  Tensile Data for the Build Direction Specimens.

Figure D.3  Stress vs. Strain Data for the Build Plane Specimens.
Figure D.4  Tensile Data for the Build Plane Specimens.
REFERENCES


