ANALYSIS OF THE LASER POWDER BED FUSION ADDITIVE MANUFACTURING PROCESS THROUGH EXPERIMENTAL MEASUREMENT AND FINITE ELEMENT MODELING

A Dissertation in
Mechanical Engineering
by
Alexander Jay Dunbar

© 2016 Alexander Jay Dunbar

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

May 2016
The dissertation of Alexander Jay Dunbar was reviewed and approved* by the following.

Pan Michaleris  
Professor of Mechanical Engineering  
Dissertation Adviser  
Chair of Committee

Timothy W. Simpson  
Professor of Mechanical and Industrial Engineering

Qian Wang  
Professor of Mechanical Engineering

Allison Beese  
Assistant Professor of Materials Science and Engineering

Karen Thole  
Head of the Department of Mechanical and Nuclear Engineering

*Signatures are on file in the Graduate School.
Abstract

The objective in this work is to provide rigorous experimental measurements to aid in the development of laser powder bed fusion (LPBF) additive manufacturing (AM). A specialized enclosed instrumented measurement system is designed to provide in situ experimental measurements of temperature and distortion. Experiments include comparisons of process parameters, materials and LPBF machines. In situ measurements of distortion and temperature made throughout the build process highlight inter-layer distortion effects previously undocumented for laser powder bed fusion. Results from these experiments are also be implemented in the development and validation of finite element models of the powder bed build process.

Experimental analysis is extended from small-scale to larger part-scale builds where experimental post-build measurements are used in analysis of distortion profiles. Experimental results provided from this study are utilized in the validation of a finite element model capable of simulating production scale parts. The validated finite element model is then implemented in the analysis of the part to provide information regarding the distortion evolution process. A combination of experimental measurements and simulation results are used to identify the mechanism that results in the measured distortion profile for this geometry.
Optimization of support structure primarily focuses on the minimization of material use and scan time, but no information regarding failure criteria for support structure is available. Tensile test samples of LPBF built support structure are designed, built, and tested to provide measurements of mechanical properties of the support structure. Experimental tests show that LPBF built support structure has only 30-40% of the ultimate tensile strength of solid material built in the same machine. Experimental measurement of LPBF built support structure provides clear failure criteria to be utilized in the future design and implementation of support structure.
# Table of Contents

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

List of Figures .................................................................................. xii

Acknowledgments ............................................................................. xviii

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

  1.1 Prior work .................................................................................. 2

    1.1.1 Related Work in Welding ....................................................... 2

    1.1.2 Direct Deposition Additive Manufacturing ..................... 3

    1.1.3 Laser Powder Bed Fusion Additive Manufacturing .......... 6

  1.2 Motivation .................................................................................. 9

  1.3 Objective in this Research .......................................................... 10

  1.4 Thesis Outline .......................................................................... 11

Chapter 2. Measurement of Experimental In Situ Distortion and Temperature Measurements During the Laser Powder Bed Fusion Additive Manufacturing Process ......................................................... 15

  2.1 Introduction .............................................................................. 16

  2.2 Description of Experimental Procedure .................................... 21
Chapter 3. Analysis of In Situ Measurements of Distortion and Temperature for the Laser Powder Bed Fusion Additive Manufacturing Process

3.1 Abstract ............................................. 40
3.2 Introduction ....................................... 41
3.3 Methods ............................................. 44
  3.3.1 Measurement Equipment ......................... 46
  3.3.2 Description of Experimental Cases ................. 47
3.4 Results and Discussion ............................ 52
  3.4.1 Comparison of Ti-6Al-4V and Inconel®718 Builds .... 52
  3.4.2 Comparison Between EOS M280 and Renishaw AM 250 Laser Powder Bed Fusion Machines ............. 61
3.5 Conclusion .......................................... 66
3.6 Acknowledgments ................................... 68
Chapter 4. Experimental Validation of Finite Element Modeling for Laser Powder Bed Fusion Deformation

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Abstract</td>
<td>69</td>
</tr>
<tr>
<td>4.2</td>
<td>Introduction</td>
<td>70</td>
</tr>
<tr>
<td>4.3</td>
<td>Experiment</td>
<td>73</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Experimental Setup</td>
<td>73</td>
</tr>
<tr>
<td>4.3.1.1</td>
<td>Description of Experimental Builds</td>
<td>74</td>
</tr>
<tr>
<td>4.3.1.2</td>
<td>Description of Measurement Equipment</td>
<td>78</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Experimental Results</td>
<td>79</td>
</tr>
<tr>
<td>4.4</td>
<td>Powder Bed Fusion Simulation</td>
<td>85</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Thermal Analysis</td>
<td>85</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Mechanical Analysis</td>
<td>86</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Numerical implementation</td>
<td>88</td>
</tr>
<tr>
<td>4.5</td>
<td>Results and Discussion</td>
<td>92</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Model Comparison To Experimental Measurements</td>
<td>92</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Substrate Deformation</td>
<td>97</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Extension of Rotating Scan Pattern Case</td>
<td>102</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Distortion Evolution in Time</td>
<td>104</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusion</td>
<td>111</td>
</tr>
<tr>
<td>4.7</td>
<td>Acknowledgments</td>
<td>111</td>
</tr>
</tbody>
</table>

5.1 Abstract .................................................. 113
5.2 Introduction ............................................. 114
5.3 Description of Experimental Procedure .......... 116
  5.3.1 Design of Experimental Test Pieces .......... 116
  5.3.2 Processing parameters .......................... 121
  5.3.3 Measurement Procedure ....................... 122
5.4 Results and Discussion .............................. 123
5.5 Conclusion ............................................. 136
5.6 Acknowledgements .................................... 137

Chapter 6. Conclusions And Future Work ............... 138

6.1 Conclusions ............................................. 138
6.2 Future Work ........................................... 140

References ................................................. 142
List of Tables

2.1 Description of experimental cases ........................................... 30
2.2 Post-process measurements of the cases ................................ 36

3.1 Description of experimental cases ........................................... 51
3.2 Post-process measurements for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) .......................................................... 57
3.3 Post-process measurements for Case 3 (Ti-6Al-4V) and Case 4 (Inconel® 718) .......................................................... 60
3.4 Post-process measurements of Case 1 (EOS M280) and Case 5 (Renishaw AM250) .......................................................... 66

4.1 Description of Experimental Cases ........................................... 78
4.2 Case 1 (rotating scan pattern) peak distortion comparison by percent deviation with experimental measurements .......................... 82
4.3 Case 2 (constant scan pattern) peak distortion comparison by percent deviation with experimental measurements .......................... 83
4.4 Temperature dependent thermal properties of solid Inconel® 718 [1,2] .......................................................... 88
4.5 Temperature dependent mechanical properties of solid Inconel® 718 [3] .......................................................... 89
4.6 As-used constant material properties and processing conditions .......................................................... 89
4.7 Comparison of experimental measurements and simulation results for Case 1 (Rotating scan pattern). The error is averaged at each nodal location in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by the experimental distortion measurement at each height.

4.8 Comparison of experimental measurements and simulation results for Case 2 (Constant scan pattern). The error is averaged at each node in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by experimental distortion measurement at each height.

4.9 Comparison of experimental measurements and simulation results for Case 2 (Constant scan pattern) with and without a flexible substrate. The error is averaged at each node in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by experimental distortion measurement at each height.

5.1 Description of tensile samples.

5.2 Description of experimental cases (NA - Not Applicable).

5.3 Averaged Results for Tensile Tests.
5.4 Percent reduction in the measured support structure material (Equation 5.3) at the solid material support structure interface (SMSSI) and 1 mm above the SMSSI
List of Figures

2.1 The *vault* an experimental enclosure designed for use of experimental measurements in LPBF machines ........................................... 22

2.2 Schematic showing both the top and side view of testing substrate ..... 23

2.3 Substrate supports and DVRT ........................................... 24

2.4 Experimental setup with a post-build substrate attached ............... 24

2.5 The *vault* attached to the build plate in a LPBF machine .......... 25

2.6 The *vault* lowered into testing position in a LPBF machine ........ 26

2.7 Schematic of the AM build and the measurement equipment location ... 28

2.8 Scan pattern schematic (a) Case 1 - Rotating scan pattern, (b) Case 2 - Constant scan pattern ........................................... 29

2.9 Comparison of the distortion in the Z direction in LPBF builds using rotating and constant scan patterns ........................................... 31

2.10 Sample distortion process (Powder spread → Laser melting → Cooling) as recorded by the DVRT ........................................... 32

2.11 Schematic of the distortion cycle during LPBF process (Corresponds to Figure 2.10 (a)-Powder Spread (b)-Laser Melting (c)-Cooling) .......... 33

2.12 Comparison of the distortion in the Z direction accumulated by the LPBF builds using rotating and constant scan patterns - first three layers .... 34
2.13 Comparison of the in situ temperature measurements for rotating and constant scan pattern during LPBF processing ................. 34

3.1 The vault experimental enclosure designed for measurements in LPBF machines ................................................. 45

3.2 The vault being lowered into a LPBF machine ......................... 46

3.3 Schematic showing both top and side view of substrate used in Cases 1, 2 and 5 with prescribed build area ................................. 47

3.4 Schematic showing both top and side view of substrate used in Cases 3 and 4 with prescribed build area ................................. 48

3.5 Build and measurement layout schematic for different experimental cases ................................................................. 49

3.6 Completed builds of Case 4 (similar geometry to Case 3) and Case 1 (similar geometry to Case 2 and 5) ........................................ 50

3.7 Schematic demonstrating the distortion evolution process with build phases (Regions: Grey - Powder spread, Red- Laser melting, and Blue - Cooling) .................................................. 53

3.8 Comparison of distortion in the Z direction for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) using a 0.82mm thick substrate .................... 54

3.9 Comparison of distortion in the Z direction for the early layers of Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) using a 0.82mm thick substrate .... 54

3.10 Comparison of temperature measurements for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) built using a 0.82mm thick substrate .............. 56
3.11 Comparison of temperature measurements for the early layers of Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) built using a 0.82mm thick substrate 56

3.12 Comparison of distortion in the Z direction for Case 3 (Ti-6Al-4V) and Case 4 (Inconel® 718) built using a 3.20mm thick substrate 58

3.13 Comparison of temperature measurements for Case 3 (Ti-6Al-4V) and Case 4 (Inconel® 718) built using a 3.20mm thick substrate 59

3.14 Comparison of distortion in the Z direction for Case 1 (EOS M280) and Case 5 (Renishaw AM50) built using a 0.82 mm substrate 62

3.15 Comparison of temperature measurements for Case 1 (EOS M280) and Case 5 (Renishaw AM50) built using a 0.82 mm substrate 62

3.16 Comparison of distortion in the Z direction in the early layers using Ti-6Al-4V for Case 1 (EOS M280) and Case 5 (Renishaw AM250) built using a 0.82 mm substrate 64

3.17 Comparison of temperature measurements in the early layers using Ti-6Al-4V for Case 1 (EOS M280) and Case 5 (Renishaw AM250) built using a 0.82 mm substrate 65

4.1 Schematic of the both deposition and the substrate for: (a)-Case 1 (rotating scan pattern) (b)-Case 2 (constant scan pattern) 75

4.2 Completed build with substrate for: (a)-Case 1 (rotating scan pattern) (b)-Case 2 (constant scan pattern) 76
4.3 Schematic of the scan pattern for: (a)-Case 1 (Rotating Scan Pattern)  
(b)-Case 2 (Constant Scan Pattern) .................................................. 77

4.4 Schematic of CMM measurement locations for Case 1 and 2 .............. 79

4.5 Distortion measurement results along the four measurement locations for  
both Case 1 (rotating scan pattern) and Case 2 (constant scan pattern) .... 81

4.6 Sensitivity of post-build distortion to FE model convection coefficient for  
constant scan pattern case (Case 2) .................................................... 90

4.7 Mesh used for: (a)-Case 1 (rotating scan pattern) simulation (b)-Case 2  
(constant scan pattern) simulation ....................................................... 91

4.8 Averaged CMM measurements of post-build distortion compared against  
FE model results at the four measurement locations shown in Figure 4.4 .... 93

4.9 Measurement location for in situ distortion measurements in the build  
direction (Z) during the build process .................................................. 98

4.10 Comparison of experimental and FE model results for distortion of the  
substrate in the build direction ......................................................... 99

4.11 Distortion results for simulation of Case 2 (Constant Scan Pattern) with  
and without a flexible substrate for each of the four measurement locations  
shown in Figure 4.4 ........................................................................... 100

4.12 Extension of the rotating scan pattern case to full build size for the four  
measurement locations shown in Figure 4.4 ....................................... 103
4.13 Contour plots of distortion in mm (distortion magnified 10x) for: (a)-Case 1 (rotating scan pattern) halfway through build (b)-Case 1 (rotating scan pattern) finished build after part has cooled to ambient temperature (c)-Case 2 (constant scan pattern) halfway through build (d)-Case 2 (constant scan pattern) finished build after part has cooled to ambient temperature ........................................... 105

4.14 Comparison of the current part height and peak distortion height versus time for the negative X measurement location for Case 2 (constant scan pattern) ......................................................... 106

4.15 Comparison of the distortion of the top layer and the peak distortion value versus time for the negative X measurement location for Case 2 (constant scan pattern) ......................................................... 107

4.16 Case 2 (constant scan pattern) contour plots of Cauchy stress in MPa (distortion magnified 2.5x) for: (a)-Cauchy XX stress halfway through build halfway through build (Z=6.3 mm) (b)-Cauchy YY stress halfway through build (Z=6.3 mm) (c)-Cauchy XX stress for finished build (d)-Cauchy YY stress for finished build ......................................................... 109

5.1 Schematic of the tensile test specimens ......................................................... 117

5.2 Failed tensile samples that failed during the build process .......................... 118
5.3 Magnification of tensile specimen highlighting the post-build machining required to remove solid material for testing of support structure

5.4 Example of each of the 4 tensile sample types

5.5 Example tensile specimen after testing

5.6 A representative stress versus strain curve for each sample type

5.7 CT scan of tensile samples first layer of the support structure: (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4

5.8 CT scan of tensile samples 1 mm above than the bottom support structure solid material interface: (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4

5.9 Normalized percent solidified material versus part height from CT scans for Samples 1-4

5.10 Image of the support structure fracture surface from Sample 1 after tensile testing

5.11 Magnification of the image shown in Figure 5.10 highlighting the porous support structure material

5.12 Image of the support structure fracture surface from sample type 3 after tensile testing

5.13 Magnification of the image shown in 5.13 highlighting the poor fusion between the support structure and solid material
Acknowledgments

I would like to thank my family for support and encouragement throughout my time in graduate school.
Chapter 1

Introduction

In recent years, additive manufacturing (AM) has seen a large growth in utilization. The adoption of AM is directly related to interest in producing parts with higher complexity than is feasible using traditional manufacturing processes. Additive manufacturing allows parts to be built from the ground producing the capability for internal structures and geometries that would be otherwise unattainable. Many different forms of additive manufacturing exist, each with their own pros and cons. AM methods such as laser directed energy deposition (LDED) and electron beam additive manufacturing (EBAM) methods allow for larger parts to be made much faster, but at the cost of dimensional accuracy. Parts made using LDED or EBAM are typically described as near-net shape parts, describing the frequent need for post-build machining. In contrast, laser powder bed fusion (LPBF) is capable of constructing parts within within tighter tolerances than previously mentioned AM methods, but it is typically limited to a smaller build volume.

Laser powder bed fusion is a newer method of metal based additive manufacturing, as a result it has become an extremely active research field. As with most metal-based additive manufacturing methods, extreme temperatures during the build process result in residual stresses which cause failed builds and post-build distortion. Tuning of build
processes parameters and post-process treatments can help correct distorted geometry and residual stress, but current methods to determine ideal build parameters rely on a trial and error method, that must be explored for each new material and part geometry. Experimental builds are designed and carried out as part of this research to quantify effects of processing parameters, build material and LPBF machine on final build quality and to provide insight into the evolution distortion during the build process. In addition to furthering the understanding of the LPBF AM process, experimental results produced as part of this work will provide validation data to aid in the development of Finite Element (FE) models and analysis of the LPBF build process with the goal of optimizing build process parameter selection.

1.1 Prior work

1.1.1 Related Work in Welding

As a result of the similarities between welding and additive manufacturing, it is not surprising that much of the research currently being performed on additive manufacturing is paralleled by welding research. As with additive manufacturing, a common areas of research include prediction of final part geometry and reduction of part distortion and thermally driven residual stress. Thermo-mechanical FE models for welding have a long history of utility many which predate additive manufacturing [4–13]. Early models, such as Hibbitt and Mercal [4], focus on prediction of distortion from simple bead on plate welds.
Later models expand from 2D post process analysis to 3D transient coupled heat and thermos-elasto-plastic analysis capturing stress and strain during the weld process [9–11]. Other advancements include the modeling material phase change and the prediction of out of plane distortion modes [14–16]. Lindgren has produced a detailed summaries of much of the FE modeling of welding highlighting information ranging from computational analysis to weld model complexity and material modeling [17–19].

Each of the afore mentioned models highlight the importance and utility that FE modeling brings to the understanding of the welding process. A caveat of the implementation of simulation in research is that for a model to provide useful analysis, it must first be validated. Experimental measurements provide the primary form of validation for these models as theoretical solutions are rarely available. Past publications have highlighted the importance of experimental work in the development of analytical models [11, 19–26]. Once validated, computational models allow for extended analysis, especially in situations where direct measurement is unfeasible [20, 24]. The works highlighted here demonstrate the necessity of experimental work in the development of a computational model and serve to emphasize the utility of in situ data for model validation.

1.1.2 Direct Deposition Additive Manufacturing

Experimental work in alternate methods of additive manufacturing

Experimental analysis of new manufacturing methods is crucial to both understanding the physics of the process and its optimization. The implementation
of directed energy deposition has benefited greatly from understanding gained from experimental analysis. Thermal measurements from Peyre et al. [27] are used to measure the heat effected zone and which are then implemented in a model validation for direct energy deposition experimental build. Another study, implemented non-contact digital image correlation (DIC) to provide in situ strain measurement to help determine the effects of certain process parameters effects on build geometry [28]. Lundback and Lindgren [29] utilized in situ experimental measurements of both displacement and temperature to aid in the development and validation of FE model which is now Volvo Aero. The utility of this work to the LDED manufacturing process this work provides incites the need for similar experimental measurements of the LPBF build process.

Parametric analysis of different AM methods allows for the suggestion of build parameter variation to reduce overall build distortion [10, 30–37]. Several studies have demonstrated that minimization of total heat input to the part will help reduce distortion [10, 30], but for certain materials this may have an opposite effect [36, 38]. Other studies [30–32], show that by preheating a part, the thermal gradient in the part is reduced thereby hindering the development of residual stress in the part. For some materials, the addition of dwells has been shown to reduce residual stress and build distortion, whereas for others, dwells increase distortion accumulation [36]. The discrepancies in each of these studies highlights the complexity of the additive manufacturing build process and demonstrates the need for thorough research in development of recommendations for the improvement of the build process.
Finite element model development for additive manufacturing

Experimental analysis is important to the increased understanding of the effect build parameters and materials variation has on the final quality of AM made parts, but often experimental studies are prohibitively expensive. Just as with welding research, implementation of modeling software in additive manufacturing research has been instrumental in improving the builds and reducing distortion in AM built parts [10, 31, 37, 39–44]. Denlinger et al. [45] were able to provide a parametric analysis to determine best practices in distortion reduction for a large part that would be prohibitively expensive to perform trial and error experimental studies on. Modeling is also be useful in the isolation of specific material properties, which can be used to determine the effect each has on the build process. By simulating a build with and without the phase transformation in Ti-6Al-4V, Denlinger et al. [36] were able to show that the inclusion of dwell times actually increases distortion, whereas in Inconel® 718 the same dwells reduce distortion. Hoadley and Rappaz [44] utilized a FE model of laser cladding in the analysis of clad thickness and processing speed and their effect on temperature field. Another model [46], provides analysis of the solidification of molten metal droplets, providing insight into the solidification process present in AM. These FE models demonstrates the unique ability of computational analysis provides to the field of AM.
1.1.3 Laser Powder Bed Fusion Additive Manufacturing

Experiments for laser powder bed fusion

Experimental results are available for laser powder bed fusion, studying varying aspects of the build process including: scan patterns, laser speed and power, melt pool size, and materials using an assortment of different measurement techniques [34, 47–50]. Effects of laser scan pattern and speed have been made using post-process measurements of distortion to determine which parameters reduce final build distortion [48]. Another study compared differing scan patterns, measuring their effect both a bare plate and a plate with a single layer of powder by measuring post-build distortion [51]. Morgan et al. [49] provided a qualitative analysis of varying process parameters, most notably the effect of laser pulse frequency, power, scan speed, hatch spacing, and scan length on numerous single layer coupons to identify each parameters effects on microstructure. Most experimental studies performed in LPBF are limited to either post-process analysis. The build process for powder bed additive manufacturing is comparatively complex when compared with many directed deposition methods of AM. The complexity is compounded by the fact that for LPBF, all but the top layer of the part is obscured by powder during the build process, which precludes the use of many common measurement techniques.

As a result of the increased complexity in the build process, measurement techniques for LPBF require ingenuity to be able to provide experimental results of the same caliber as other forms of AM. For example, a recent study demonstrated a technique wherein
measurements of the melt pool are made by aligning a camera with motors used to move the laser beam during the laser scanning process [52]. Experimental measurements were made on single track build to determine how process parameters affect the melt pool. Experiments have also been performed to aid modeling work by analyzing melt pool dynamics during the build process [53]. Other LPBF experiments have focused on determining the effect of process parameters variation on microstructure [54]. Work outline here demonstrates the limited range of experimental measurements that have been taken of LPBF. Experimental measurements are primarily limited to post-build analysis [55,56], with few able to capture in situ thermal analysis [57] or in situ melt pool analysis [52].

**Laser powder bed fusion modeling**

The use of FE modeling for additive manufacturing and welding has shown to be helpful in the field of build failure mitigation [14,31,37,39], and so the extension of direct deposition models to LPBF is understood, similar to the extension of welding modeling to direct deposition forms of AM [10,19]. For LPBF, the heat source and layer thickness are significantly smaller than in direct deposition by several orders of magnitude [58]. In addition, typical models utilize commercial FE modeling packages to simulate the LPBF build process [55,56,59,60], most of which are not optimized for additive manufacturing. Subsequently, most of these models are limited to capturing only a small build area of only a few layers accurately [56,57], or modeling the addition of several layers at once [60,61], which without proper consideration could lead to misleading results.
Many of the models developed for LPBF show limited or no experimental validation [55–57, 59–63]. In many cases the lack of experimental validation is the result of limited experimental analysis for LPBF and difficulty in producing experimental results that would provide a sufficient validation to demonstrate accuracy of the model. As shown with direct deposition models, in situ experimental results will provide the best validation as it will demonstrate the models ability to capture the whole build process giving insight to distortion accumulation instead of just the post-build information.

**Support structure for laser powder bed fusion**

As a consequence of the layer-wise construction of parts in LPBF, implementation of support structure is often required for contain overhanging geometries design that typically result in collapse or large scale distortion [64]. Optimization of support structure is an active field of research as material used in the construction of support structure is wasted as it must be removed post-build [65–68]. Ideally, support structure is kept to a minimum while still producing a successful build. Much of the research focuses on production of ideal support structures and optimizing ease of part remove post-build [65, 67, 68]. However, studies thus far have not performed experimental analysis of support structure mechanical properties to identify failure criteria. A finite element model (FEM) was developed by Krol et al. [68] wherein simulations of different support structures could be examined and compared against one another for optimization purposes, but no validation is performed
on this study. While these studies provide guides for support structure design, there is scant quantitative analysis focusing on support structures for LPBF AM.

1.2 Motivation

Laser powder bed fusion is an expensive method of manufacturing due to the cost of materials and the high vulnerability to build failure. While LPBF is capable of producing net shape parts with intricate inner structure, the same complexity in part geometry that powder bed additive manufacturing was designed for is often plagued with large scale distortion and residual stresses. A major obstacle in the advancement of the LPBF manufacturing method is a scarcity of robust experimental measurements which result in unclear techniques for build failure mitigation. Often, methods that will reduce residual stresses in one material will increase stresses in another. As a result, each build requires trial and error parametric studies for each material and part geometry thereby increasing the overall cost of manufacturing.

Numerous sets of experimental builds necessary to produce successful parts rapidly increases the cost of LPBF AM to the point where its utility becomes eclipsed by its cost. Instead of relying solely on trial specific experimental analysis, understanding of the build process based off of generalized experimental analysis is suggested. In addition to furthering understanding of the physics inherent in the LPBF build process, experimental data produced from these experiments provides necessary experimental results for future model validation. Simulation of AM processes have proven to be successful in reducing
build costs by providing expansive parametric analysis with computer time being the only consumed resources.

1.3 Objective in this Research

The goal in this research is to design and perform experiments of the laser powder bed fusion build process. Experimental measurements include both in situ and post process data with the intent of aiding the development and validation finite element modeling software for LPBF. Measurements are taken for a series of experiments comparing materials, process parameters, build geometries, and LPBF machines.

For this work, it was necessary to develop a system that is capable of producing in situ measurements of the LPBF without altering the build process or parameters. Once completed, the enclosed measurement system was implemented in LPBF machines to help provide insight to the AM build process. Experimental builds range from small test builds to full scale parts to provide accurate measurements for all scales of LPBF. Small part geometry builds are designed to aid the development and validation of FE models. Part scale builds are utilized in the validation of a FE model that designed specifically for use with LPBF additive manufacturing. Mechanisms present in LPBF additive manufacturing identified by small scale builds can be utilized and scaled for use with larger component sized geometries.

Experimental test pieces are built to provide quantitative analysis of the mechanical properties of LPBF built support structure. Proper implementation of support structure
can reduce the chance of large scale distortion and build failure in laser powder bed fusion. Measurement of support structure mechanical properties is imperative in the process of support structure optimization. Measured mechanical properties can be utilized in future models to identify potential build failure saving both time and money.

Experiments are designed with the goal of improving the quality and availability of measured results for LPBF. Measurements made as part of this study provide novel insight to the evolution of distortion for LPBF made components. Models developed using the experimental measurements produced from this research can be used to improve build quality for LPBF AM parts. By extending the modeling capability of LPBF AM builds, effective cost will be reduced making additive manufacturing more accessible. Modeling will also help designers gain a better understanding of the build process and help to isolate features that may cause build failures.

1.4 Thesis Outline

The topics covered in the thesis are outlined next. Each experiment is defined, and its utility to the overall objective is highlighted\textsuperscript{1}.

Chapter 2: Measurement of Experimental In Situ Distortion and Temperature Measurements During the Laser Powder Bed Fusion Additive Manufacturing Process

\textsuperscript{1}At the time of submission, Chapters 2, 3, and 4 are manuscripts currently under review at the journal Additive Manufacturing
1. Novel measurement equipment and techniques are implemented to allow for in situ distortion and temperature measurements during the build process. Measurement equipment is designed to allow for measurements to be taken while the powder bed system operates in default configuration.

2. In situ measurements of the LPBF build process are completed comparing distortion and temperature for experimental builds comparing the use of a rotating and constant scan pattern.

3. Measurements made as part of this study demonstrate the increased distortion (37.6%) caused by implementation of a constant scan pattern.

4. In situ measurements demonstrate the previously measured distortion evolution throughout the build process. Non-constant distortion accumulation through the build process identifies problems with some current LPBF modeling techniques.

Chapter 3: Analysis of In Situ Measurements of Distortion and Temperature for the Laser Powder Bed Fusion Additive Manufacturing Process

1. Five experimental cases are measured using the previously constructed measurement system for further analysis of the LPBF build process.

2. Comparisons are made utilizing in situ measurements of distortion and temperature during the build process for experimental builds built using Inconel® 718 and Ti-6Al-4V for two different geometries.
3. Experimental results comparing materials demonstrate the complexity of the LPBF build process by highlighting the difference in distortion evolution and final part geometry.

4. Direct comparisons are made between experimental builds produced using the EOS M280 machine and the Renishaw AM250. In situ results of distortion and temperature for components built in two common LPBF machines helps identify strengths and weaknesses of each machine.

5. Differences in both final build and distortion evolution measurements further demonstrates the complexity of implementation of distortion mitigation techniques.

6. Measurements made as part of this study provide experimental results for validation of future FE models providing comparisons for variable build material, part geometry and powder bed machine.

Chapter 4: Experimental Validation of Finite Element Modeling for Laser Powder Bed Fusion Deformation

1. Two experimental builds of cylindrical geometry, one using a rotating scan pattern and the other using a constant scan pattern, are designed and constructed to provide post-build distortion measurements.

2. Post-build measurements of part distortion are used to compare and contrast the two cases.
3. FE modeling software (CUBES®) is validated using post-build measurements of distortion.

4. FE model is utilized to provide information about the distortion evolution throughout the build process.

5. Simulation results demonstrate that for these geometrise distortion in the current layer is caused by cumulative effect of subsequent layers solidifying and compressing the material beneath it.


1. Tensile tests are performed with the goal of measuring the ultimate tensile strength of LPBF built support structure

2. Tensile test samples are built with box type support structure with varied hatch spacing to test the effect on increased material on overall support structure strength

3. CT scans of tensile samples are made to provide insight to the fidelity of the internal geometry of the support structure.

4. Experimental measurements show that the ultimate tensile strength of LPBF support structure is 30-40% of solid material.
Chapter 2

Measurement of Experimental In Situ Distortion and Temperature Measurements During the Laser Powder Bed Fusion Additive Manufacturing Process

Measurements of the temperature and distortion evolution during laser powder bed fusion (LPBF) are taken as a function of time. In situ measurements have proven vital to the development and validation of FE models for LPBF. Due to powder obscuring all but the top layer of the part in LPBF, many non-contact measurement techniques used for in situ measurement of additive manufacturing processes are impossible. Therefore, an enclosed instrumented system is designed to allow for the in situ measurement of temperature and distortion in an LPBF machine without the need for altering the machine or the build process. By instrumenting a substrate from underneath, the spread powder does not affect measurements. Default processing parameters for the EOS M280 machine prescribe a rotating scan pattern of $67^\circ$ for each layer. One test is completed using the default rotating scan pattern and a second is completed using a constant scan pattern. Experimental observations for the build geometry tested showed that for Inconel® 718 and a constant scan pattern produce results in a 37.6% increase in distortion as compared with

\footnote{Under Review at the journal Additive Manufacturing}
a rotated scan pattern. The in situ measurements also show that the thermal cycles caused by the processing of a layer can impact the distortion accumulated during the deposition of the previous layers. The amount of distortion built per layer between the rotating and constant scan pattern cases highlights inter-layer effects not previously discovered in LPBF. The demonstrated inter-layer effects in the LPBF process should be considered in the development of thermo-mechanical models of the LPBF process. Part 1 of this work details the development of a measurement system designed for implementation in laser powder bed fusion additive manufacturing machines. Part 2 expands the number of experimental cases including comparisons of build materials and LPBF machines.

2.1 Introduction

The laser powder bed fusion (LPBF) additive manufacturing (AM) process produces parts from computer-aided-design (CAD) 3D models. First, the CAD model is split into a series of 2D layers where a laser path and power settings can be defined. For the build process, a thin layer of powder is spread evenly across the build area, then a laser selectively melts the material for that layer which in turn cools and solidifies to form a dense geometry. Layers in powder bed systems are built on the scale of 10-100µm, allowing LPBF to produce net shape parts. While powder bed systems are capable of producing more accurate parts than other AM processes, large thermal gradients are still present, resulting in unacceptable levels of residual stress and distortion which often cause part failure. Typically, these failures are resolved by a trial and error process wherein
processing parameters are changed until a successful build is produced. This process can be costly when including the cost of machine time and material. In order to avoid the trial and error approach, a greater understanding of how residual stress and distortion are accumulated through LPBF processing is required. In situ measurements will allow for a greater understanding of the LPBF process.

Several different groups have performed experiments on powder-bed machines focusing on varying aspects of the build process including: scan patterns, laser speed, laser power, and melt pool size using a variety of experimental methods. Pohl et al. [48] performed a series of experiments varying laser scan pattern and speed for a single layer of powder. Post-process experimental deflection measurements were then used to inform which parameters reduce distortion. Kruth et al. [51] presented post-process distortion measurements of parts built in a powder-bed machine. Distortion effects from differing scan patterns for both single layer builds and bare plates were compared in order to select proper processing parameters in LPBF. Kempen et al. [52] have demonstrated a technique to provide in situ melt pool characterization during the LPBF process. Several single track tests were completed to determine the ideal processing parameters. The processing parameters were then applied to the manufacture of part scale builds. Post-process tensile and micro-hardness measurements are made of the full build which are then compared against high pressure die casting. The experimental results from these studies are useful in understanding the AM powder-bed process, but they also highlight the limited availability of in situ measurements.
Modeling for the powder-bed AM field has become increasingly popular, as shown by Witherell et al. [69], due to the high cost of performing experiments and a desire to avoid the trial and error approach to the successful manufacture of parts. Paul et al. [60] presented a 3D thermo-mechanical FE model to estimate the effect of thermal distortion of powder-bed AM. The effects of part orientation in the LPBF process are measured, but no direct experimental validation is completed. An ANSYS model used by Dai and Shaw [59] is capable of simulating a powder-bed AM process but, the results shown present only two layers and do not provide any validation. Some of the model developers have used experimental results to validate their models. In an earlier paper from Dai and Shaw [33], an ANSYS model is used to demonstrate how laser scanning patterns can affect distortion. The paper demonstrates that using a spiral laser scan path can reduce distortion in a build. Li, R [55] applied an ANSYS model to analyze the effects of differing processing parameters on temperature in powder-bed systems and compared the simulation results against post-process experimental measurements. The experimental results used for the validation study are made post-process by measuring track width from single lines of varying scan speeds. Cheng et al. [57] presented a model that matches well with experimental data focused primarily on thermal characteristics of powder-bed electron beam additive manufacturing. King et al. [61] presented several different models of varying scales ranging from powder and microstructure scale to full scale part modeling in LPBF. Post-process measurements of final distortion are compared against simulation results. Song et al. [56] use an Abaqus FE model of a powder-bed system to simulate strain
in a 2D 15 layer build. This model is validated against x-ray diffraction measurements of the horizontal strain component along a horizontal line in the build. The model presented is capable of matching in order of magnitude and trend of the measured strains. Due to the difficulty in implementing measurement equipment in a powder-bed system, validation data comes from either non-contact thermal measurements or post-process distortion or stress measurements. To date, no LPBF mechanical model has been validated against in situ distortion measurements.

While it is common to validate a FE model against post-process distortion measurements, this practice does not provide insight into the process physics. The usefulness of in situ measurements for model validation of AM processes has been clearly demonstrated in several previous studies. Denlinger et al. [36] recorded in situ distortion measurements during the laser direct energy deposition (LDED) processing of Ti-6Al-4V. The results showed that due to the solid state phase transformation present in the alloy, distortion does not build consistently during deposition. Without in situ measurements, this phenomenon would have gone undiscovered. Heigel et al. [40] utilized in situ measurements of the LDED process to demonstrate the significance of convection in FE models. Several convection boundary conditions were compared to experimental measurements to determine which most accurately predicted the LDED AM process. In another paper, Heigel et al. [41] performed a parametric study of the LDED cladding process. The in situ measurements along with the post-process measurements provided by this study increase the understanding of how distortion is built in LDED processes.
Gouge et al. [42] implemented a convection model for FE analysis of the LDED process. Experimental measurements of convection coefficients are used in the development of a convection model which is compared against in situ thermocouple measurements. Peyre et al. [27] used in situ thermocouple measurements to provide a validation of their thermal model of a direct metal deposition experiment. A non-contact digital image correlation (DIC) in situ strain measurement was used in Ocelik et al. [28] to motivate the selection of processing parameters. Lundbck and Lindgren [29] utilized in situ experimental measurements for both displacement, made using the ARAMIS optical system, and temperature, made using a pyrometer, in the validation of their model. The validation provided by the in situ measurements was integral in the development of the model now used at Volvo Aero. None of these works, demonstrating the importance of in situ measurement, have focused on LPBF processes.

Due to the practicality of the LPBF process no in situ experimental measurements of distortion are currently available. The primary obstacle in capturing these measurements is the powder from each layer which covers the entire part. This makes many in situ measurement techniques, such as laser displacement sensor (LDS) measurements impossible. Thus far, thorough model validation of the LPBF process has been impossible due to difficulty of in situ measurements. Therefore, an enclosed instrumented system, henceforth referred to as the vault, capable of providing in situ measurements of the LPBF process is designed, built and demonstrated. The vault is designed to be placed inside of the LPBF machines without requiring machine modification or the changing of the build
process. Substrates are attached at the top of the vault with minimal contact to reduce measurement interference. Instrumentation equipment inside the vault is attached to the underside of the substrate to measure distortion and temperature during the LPBF process without affecting the build process or being obscured by powder. The temperature of the substrate is measured using K-Type thermocouples, and the distortion is measured with a differential voltage reluctance transducer (DVRT). Using the in situ experimental results, a comparison of constant and rotating scan pattern is completed to show the effect of the scan pattern on the accumulation of distortion during a multi-layer LPBF build process. The time-dependent experimental results produced from these experiments allows for a greater understanding of LPBF processing parameters and the effects that they have on distortion accumulation.

2.2 Description of Experimental Procedure

2.2.1 Experimental Setup

Due to the combustibility of the metal powder used in the LPBF process the build chamber of the LPBF machine must be filled with inert gas to prevent fires and oxidation of the material. To keep the build chamber sealed, no measurement equipment or wires can breach the seal that surrounds the LPBF chamber without significantly altering the machine. Therefore it was determined that all experimental equipment must be inside of the machine during the entire build process. In addition, during the LPBF process only
the top layer is visible as powder will cover the build area on each layer. For these reasons, the *vault*, an enclosed instrumented system, is designed to be used in LPBF machines. The *vault* is designed to bolt into the build plate of several different the LPBF machines without requiring modification to the machine. Additionally, the *vault* is designed such that the LPBF machines can operate without alteration of operating conditions and processing parameters. The *vault*, shown in Figure 2.1, is designed so that all measurement equipment can be placed inside of the machine while still keeping it separated from the metal powder.

Fig. 2.1: The *vault* an experimental enclosure designed for use of experimental measurements in LPBF machines
As powder is spread across the entire build area, the build is completely obscured except for the top layer. As a result, measurements of the process must be made from underneath the build. A substrate, highlighted in Figure 2.1, is attached to the top of the vault and is now used as the build plate. A schematic of the substrate and build dimensions are shown in Figure 2.2.

![Schematic showing both the top and side view of testing substrate](image)

Fig. 2.2: Schematic showing both the top and side view of testing substrate

Two restraining bolts hold the substrate down from the center of the plate at each end. The substrate is supported in the four corners by cone head set screws. The four set screws are used to offset the substrate thereby allowing room for unrestricted distortion beneath. The cone head set screws provide sufficient support with minimal contact to the substrate. The supports for the substrate are shown in Figure 2.3. Figure 2.4 shows the experimental
setup with the substrate attached. A thin substrate, 0.81 mm thick, is used to maximize distortion from the build.

Fig. 2.3: Substrate supports and DVRT

Fig. 2.4: Experimental setup with a post-build substrate attached
Figure 2.5 shows the *vault* attached to the build plate inside of the LPBF machine. Figure 2.6 shows the *vault* lowered to testing position. The *vault* is lowered until the substrate is at the build height.

Fig. 2.5: The *vault* attached to the build plate in a LPBF machine
2.2.2 Measurement Equipment

All measurement equipment must be placed inside the vault to separate the metallic powder from the electronics. Distortion measurements are completed using the M-DVRT-3 Lord Microstrain differential variable reluctance transducer (DVRT) displacement sensor. The DVRT displacement sensor is connected to a DEMOD-DC 2 signal conditioner which converts displacements into voltages. The voltages are measured by a National Instruments USB-6009 voltage data acquisition (DAQ) system. The combined accuracy of these components is 0.5%, resulting in a ±7.5 µm error. The DVRT is used to produce in situ measurements of the displacement in the build direction throughout the build process. Temperature measurements are completed using K-Type thermocouples (TC) which have an accuracy of ±2.2°C or ±0.75% whichever is greater. Thermocouple measurements are
measured using a National Instruments 9213 DAQ system. Post-build measurements are made using Mitutoyo digital calipers which are accurate to ±0.025 mm.

The results from both DAQ systems were recorded using a small low power computer placed inside the *vault*. All measurement equipment is attached to the underside of the substrate to prevent obstruction of the LPBF build process. The measurement locations for each test are shown in Figure 2.7. Measurement locations are ideal placement. The DVRT is restrained using bolted equipment, therefore its location is considered accurate up to ±0.025 mm. Thermocouples are attached by hand, error for these locations is within ±0.75 mm of the indicated location.
Fig. 2.7: Schematic of the AM build and the measurement equipment location

### 2.2.3 Processing Parameters

Tests are completed using the EOSINT M 280 AM machine. A CAD file describing both build dimensions and location is loaded into the machine where it is cut into layers. For both the powder and the substrate Inconel® 718 is selected for its high weldability and common use in LPBF AM. Inconel® 718 powder with a diameter of $30.368 \pm 7.22 \mu m$, purchased from EOS, is used. Machine parameters default to a layer thickness of $40 \mu m$ for Inconel® and a hatch spacing of $110 \mu m$. The laser is a 4LR-400-SM-EOS and operates
at a wavelength of 1060 – 1100 nm, a power of 280 W and a travel speed of 960 mm/s. For the experiments, a build with dimensions 6.35 mm × 6.35 mm × 1.5 mm is centered on the substrate. Under normal conditions the EOSINT 280 M machine rotates the scan pattern 67° on a layer by layer basis. Case 1 completes the build using the default rotating scan pattern. Case 2 removes the rotation and instead uses a constant scan pattern. These two cases are demonstrated in Figure 2.8. The proposed tests are completed to quantify the effect that scan pattern rotation has on a build. The cases are summarized in Table 2.1.

Fig. 2.8: Scan pattern schematic (a) Case 1 - Rotating scan pattern, (b) Case 2 - Constant scan pattern
Table 2.1: Description of experimental cases

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Inconel® 718</td>
<td>Inconel® 718</td>
</tr>
<tr>
<td>Build Dimensions (mm)</td>
<td>6.35×6.35×1.5</td>
<td>6.35×6.35×1.5</td>
</tr>
<tr>
<td>Scan Pattern</td>
<td>Rotating (Figure 2.8-a)</td>
<td>Constant (Figure 2.8-b)</td>
</tr>
</tbody>
</table>

2.3 Results and Discussion

Distortion results for the Z direction (Figure 2.2) for both the constant and rotating scan pattern builds are shown in Figure 2.9.
Fig. 2.9: Comparison of the distortion in the Z direction in LPBF builds using rotating and constant scan patterns.

Figures 2.10 and 2.11 show the distortion cycle through the build process. For each layer, the build process is made up of three steps, powder spread, laser melting and then cooling, as highlighted in Figure 2.10. Figure 2.11-a shows a schematic of the substrate during the powder spreading process. When the laser is melting the powder layer, it causes a temperature gradient across the thickness of the substrate with the top of the substrate significantly hotter compared to the bottom. This temperature gradient causes the top of the substrate to expand more than the bottom which causes the center of the substrate to bow, causing distortion in the positive z direction.
This effect is demonstrated in Figure 2.11-b. As the molten layer solidifies, the cooling causes the deposited material to shrink, pulling on the substrate and forcing the substrate to bow in the opposite direction resulting in distortion in the negative z direction as shown in Figure 2.11-c.
Figure 2.12 shows the distortion for the first three layers. The first layer shows a comparable amount of distortion where the peak distortion is 0.63 mm for Case 1 and 0.68 mm for Case 2. Figure 2.9 shows that over time, the amount of distortion in each case begins to diverge. Case 1 has a final distortion of 0.85 mm. Case 2 has a final distortion of 1.17 mm representing 37.6% more distortion compared with Case 1. The inter-layer effects demonstrated here by measurements exemplify the complexity of the LPBF process.
Fig. 2.12: Comparison of the distortion in the Z direction accumulated by the LPBF builds using rotating and constant scan patterns - first three layers

Fig. 2.13: Comparison of the in situ temperature measurements for rotating and constant scan pattern during LPBF processing
Measurements of temperature versus time are found in Figure 2.13. As the result of the thermocouple attachment to underside of the substrate, sufficiently far from the build area, measurements of temperature during the build can only provide information regarding thermal saturation of the substrate. When compared to similar cases the large difference between TC1 and TC2 for Case 2 (constant scan pattern) throughout the build process was determined to be non-physical and likely the result of a poorly connected thermocouple. For both cases, the temperature measured plateaus at approximately 300 seconds. At approximately 500 seconds the build is complete and the substrate rapidly cools to room temperature. Despite the use of the rotating versus constant scan pattern used in Case 1 and Case 2, there are no perceived differences in the prescribed scan times or input energy for either case. However, comparing TC2 from both Case 1 and 2 the measured temperature in these cases begins to deviate as the build progresses.

When the substrate is distorted, the re-coater mechanism spreads additional powder, due to the bowing down of the center of the substrate, causing additional material to be built. This effect is confirmed by measurements found in Table 2.2, wherein the excess build heights match the final distortion measurements with a 2.4% and 1.7% difference for Case 1 and Case 2, respectively. Averaged throughout the build process, the excess built material results in an increased average layer thickness of 60\(\mu m\) for Case 1 (rotating) and 70\(\mu m\) for Case 2. The increased layer thickness as the result of distortion is likely the cause the previously discussed deviation of temperature measurements in Figure 2.13. As the
difference in distortion increases between Case 1 and 2 throughout the build process, the increased material results in the decreased in measured temperatures for Case 2.

Post-process measurements including the final distortion and final build dimensions can be found in Table 2.2. Excess build height is defined by the CAD build height subtracted from the final build height. Percent distortion is the amount of distortion in the measured Z direction divided by the CAD build height as shown in Equation 2.1.

\[
\%\text{Distortion} = \frac{h_{\text{distortion}}}{h_{\text{CAD}}} \times 100\%
\]  

(2.1)

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan Pattern</td>
<td>Rotating</td>
<td>Constant</td>
</tr>
<tr>
<td>CAD Build Dimensions (mm)</td>
<td>6.35×6.35×1.5</td>
<td>6.35×6.35×1.5</td>
</tr>
<tr>
<td>Final Build Dimensions (mm)</td>
<td>6.25×6.25×2.33</td>
<td>6.26×6.24×2.65</td>
</tr>
<tr>
<td>Excess Build Height (mm)</td>
<td>0.83</td>
<td>1.15</td>
</tr>
<tr>
<td>Final Distortion Measured In Situ (mm)</td>
<td>0.85</td>
<td>1.17</td>
</tr>
<tr>
<td>Percent Distortion</td>
<td>55.3</td>
<td>76.7</td>
</tr>
</tbody>
</table>
The non-constant rate of distortion and inter-layer distortion effects provided in the results help demonstrate the importance of in situ measurements in FE model validation. Recent models from King et al. [61] and Paul et al. [60] demonstrate similar approaches to part scale modeling of LPBF. To reduce computational time, these models add material in multiple layers at once. However, this method is inaccurate as inter-layer effects cannot be captured in this method. In particular, the heat cycle of the top layer affects the plasticity of previous layers. Results show that when using normal machine parameters (i.e., rotating scan pattern) some layers will add distortion while other reduce it. Therefore it is necessary to understand the accumulation of plastic strain in each layer before multiple layers can be added in a single computational step.

2.4 Conclusion

The purpose of this study is to capture in situ measurements in an LPBF machine without requiring machine modifications or changing operating conditions. To do this, an enclosed instrumented system is designed that is able to capture both temperature and distortion measurements. The experimental results show that using a constant scan pattern causes increased distortion in the build by 37.6% as compared with the rotating scan pattern for the build geometry and substrate used. Similar distortion is not expected when using a typical build plate for a LPBF machine, but the distortion in these cases can be considered an analog of residual stress in the solidified material. The amount of distortion built per layer between the rotating and constant scan pattern cases highlights inter-layer
effects not previously discovered in LPBF. For the rotating scan pattern case, distortion increases as the result of built material whereas for other layers, distortion decreases with the addition of material. Measurements of the constant scan pattern case show consistent distortion increase with each layer indicating that the reduction of distortion measured in the other case may be the result of the rotating scan pattern used. The layer-layer interaction specifically in the rotating scan pattern case emphasizes the usefulness of in situ measurements in the understanding of the LPBF process and for the validation of models. Future work includes the development of an FE model capable of capturing the inter-layer effects for full-scale part builds.

2.5 Acknowledgments

Laboratory activities conducted during this research were conducted at the Center for Innovative Materials Processing through Direct Digital Deposition at Penn State. The authors would like to thank Moog Inc. for help in planning design and execution of experiments for this work. This material is based on research sponsored by Air Force Research Laboratory under agreement number FA8650-12-2-7230 and by the Commonwealth of Pennsylvania, acting through the Department of Community and Economic Development, under Contract Number C000053981. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. Any opinions, views, findings, recommendations, and conclusions contained herein are those of the author(s) and should not be interpreted as
necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Research Laboratory, the U.S. Government, the Commonwealth of Pennsylvania, Carnegie Mellon University, or Lehigh University. The authors would also like to thank Schlumberger-Doll Research for their support of this effort. Any opinions, findings, conclusions, and/or recommendations in this paper are those of the authors and do not necessarily reflect the views of Schlumberger-Doll Research or its employees.
Chapter 3

Analysis of In Situ Measurements of Distortion and Temperature for the Laser Powder Bed Fusion Additive Manufacturing Process

3.1 Abstract

In situ experimental measurements of the laser powder bed fusion build process are completed with the goal of better understanding the distortion evolution process. Utilizing a previously designed enclosed instrumented system, five experimental builds are carried out. Experimental builds compare materials, Ti-6Al-4V and Inconel® 718, and manufacturing machines, the EOS M280 and the Renishaw AM250. A combination of in situ measurements of distortion and temperature and post-build measurements of final part geometry are used compare and contrast the different experiments. Experimental results show that builds completed using Inconel® 718 distort between 50%-80% more relative to Ti-6Al-4V depending on case. This is likely the result of the stress relaxation caused by the phase transformation inherent in Ti-6Al-4V. The experimental build completed on the Renishaw AM250 distorted 10.6% more in the Z direction when compared with

1Under Review at the journal Additive Manufacturing
the identical build completed on the EOS M280 machine. Comparisons of post-build XY cross-sectional area show a 0.3% contraction from the predefined build geometry for the Renishaw AM250 as compared with the 4.5% contraction for the part built using the EOS M280.

3.2 Introduction

Post-build part distortion is a major obstacle preventing the wide scale implementation of additive manufacturing (AM). Laser powder bed fusion (LPBF) is similar to other additive manufacturing methods (Directed energy deposition, Electron beam additive manufacturing) in that frequent part failure hampers its use at the production level. Part failures frequently come in the form of large scale deformations resulting from thermal gradients present during the additive manufacturing process. To mitigate failure, often times several builds are required utilizing a variation of build failure mitigation techniques.

Currently, there are an abundance of techniques that can be applied to reduce the distortion accumulation. Minimization of total heat input during the AM process is suggested by both Michaleris et al. [10] and Jendrzejewski et al. [30] to reduce the distortion. Applying more heat than is necessary to fully fuse the deposited material increases the thermal gradient, resulting in larger residual stresses after the part has cooled. Another suggested method for the mitigation of distortion is to preheat the part before deposition [31, 32]. Preheating increases the base temperature of the solidified material
reducing the thermal gradient between it and the melted layer thereby reducing final the residual stress and the distortion. Research has also been presented on how scan pattern can be altered to reduce the final build distortion. By using a spiraled, rather than parallel, scan pattern [33] distortion in specific directions can be reduced. Another scan pattern method for reduction of distortion suggests island scanning [34,35], wherein the laser melts small randomly selected areas across the layer to reduce peak temperatures during the build process, which also reduces residual stress development. Another study suggests that by implementing dwells between deposition passes, allowing the part to cool during the build process, can reduce final residual stress and distortion [36,38]. These methods listed are only a subsection of distortion mitigation techniques that are common to the AM field.

Seeming contradictions abound in the preceding methods of mitigating distortion in AM parts. For example one recommendation [10,30] claims that an overall reduction of heat input will reduce the distortion in the build and another [31,32] suggest supplying preheat through the substrate will also reduce the magnitude of distortion. There is no universal solution to the reduction of distortion for AM. While the mitigation techniques above have been demonstrated experimentally to aid final build distortion, another build made with different materials or build geometries may increase final distortion as compared to the default operating conditions. For AM builds using Inconel® 718, implementation of dwells between deposition passes decreased overall distortion, whereas for the same build geometry the Ti-6Al-4V build accumulates more distortion when dwells are implemented [36]. This is a result of a phase transformation mechanism present in Ti-6Al-4V [70,71] which results
in reduced final part distortion. For Ti-6Al-4V, the phase transformation occurs at high temperatures, so methods to keep the part cooler (e.g., island scanning or increased dwell times) may be detrimental.

In addition to differing material effects on final build part quality, effects of laser type can also affect final part quality. In particular, considering the primary difference between the EOS M280 and the Renishaw AM250 is the use of continuous versus pulsed laser, respectively, Santos et al. [72, 73] recommend the use of pulse laser as it reduces the size of the heat affected zone, while still providing enough heat to produce fully fused parts. However, Zhang et al. [74] demonstrate results for laser bending wherein the use of a pulsed laser causes an increase in both bending and residual stress as compared with continuous lasers. The contradiction between these two results demonstrates not only the complexity inherent in the AM processes, but also demonstrates the need for further analysis focusing on the effects of continuous versus pulsed lasers on LPBF made parts.

Many studies have been completed to develop strategies for mitigation of distortion in additive manufacturing as well as recommended processing parameters for the build process. However, significant work to define and predict the underlying causes of distortion in AM processing are less prevalent. In particular, there are few in situ comparisons of materials in laser powder bed fusion. Many of the techniques used in the mitigation of distortion for AM are process, build material, geometry and machine dependent. To better understand the evolution of distortion during the LPBF build process, several experimental builds are designed and completed to compare and contrast effects of
build geometry, materials and different LPBF machines using in situ distortion and temperature measurements. In situ experimental measurements will not only help to gain an understanding of the time evolution of distortion in LPBF but also be instrumental in the validation of modeling tools for LPBF AM.

3.3 Methods

A major challenge in the experimental design of LPBF experiments is the volatility of the powder used for manufacturing. Previous work, described in Chapter 2, details the development an implementation of an enclosed instrumented system developed to both separate the measurement equipment from the powder while still allowing for in situ measurement of the LPBF process. The enclosed system, the vault, is shown in Figure 3.1. Consistent with previous experiments, all builds are completed using interchangeable substrates \[75\]. The vault is designed to allow for measurement of the underside of an interchangeable substrate, highlighted in Figure 3.1, which is used as the build plate. In LPBF, contact measurements must be made of the underside of the substrate as the powder covers all but the top layer of the build. Wires that are attached to the top of the build will obstruct the recoater arm. Designs for the vault focused on its use without modification to the machine or alteration to the AM process.
Fig. 3.1: The vault experimental enclosure designed for measurements in LPBF machines

The build plate for these tests consists of a substrate attached to the top of the vault, Figure 3.1. The substrates are supported at each of the four corners by cone head set screws. Set screws are used to provide offset and leveling of the substrate with minimal contact to the substrate itself. The substrate is restrained by two bolts that are attached to the top plate of the vault. Figure 3.2 shows the vault being lowered into a LPBF machine.
3.3.1 Measurement Equipment

To prevent the powder from interacting with the measurement equipment, the substrate is instrumented on the underside. A differential variable reluctance transducer (DVRT) is used to measure distortion. The Lord Microstrain M-DVRT-3 is connected to a DEMOD-DC 2 signal conditioner which translates displacements into voltages which is recorded a National Instruments USB-6009 data acquisition (DAQ) system. The accuracy of these components is ±0.5% resulting in a possible ±15 µm error. The temperature is measuring using Type-K thermocouples which have an accuracy of ±2.2° C. Thermocouple measurements are taken using a National Instruments 9213 DAQ system. Results from both DAQs are recorded using a low power computer inside of the vault. Measurement locations can be found in Figure 3.5.
3.3.2 Description of Experimental Cases

The first experimental build compares two common LPBF build materials, Ti-6Al-4V (Case 1) and Inconel® 718 (Case 2). Both cases are built using the same build geometry and with the same substrate size. Dimensions of the build volume for Cases 1 and 2 are 6.35 mm × 6.35 mm × 1.5 mm. The substrate used for these tests is 89.0 mm × 26.0 mm × 0.81 mm. Figure 3.3 shows a schematic of the build and substrate geometry that is used for Cases 1 and 2. In situ measurements of temperature and distortion will give information to the distortion evolution for LPBF of Ti-6Al-4V and Inconel® 718.

![Schematic showing both top and side view of substrate used in Cases 1, 2 and 5 with prescribed build area](image)

Fig. 3.3: Schematic showing both top and side view of substrate used in Cases 1, 2 and 5 with prescribed build area
Cases 3 and 4 were completed comparing Ti-6Al-4V and Inconel® 718, respectively, using thicker substrates to measure distortion accumulation with a larger cross-sectional area. For Cases 3 and 4, a thicker substrate is also used to limit distortion to the measurable range of the DVRT. The build geometry for Cases 3 and 4 has a cross-sectional (XY) area of 31.8 mm × 31.8 mm and a build height of 0.24mm. Substrate dimensions for Cases 3 and 4 are 89.0 mm × 36.9 mm × 3.2 mm. Figure 3.4 shows a schematic of the build geometry and the substrate.

Cases 1, 2, 3, and 4 are all made using the EOS M280 LPBF machine. Another experimental build was made to explore what effects a different LPBF machines have on the distortion accumulation process. Case 5 is built using the Renishaw AM250 machine.
with Ti-6Al-4V. For Case 5, build volume and substrate geometry matches that of Cases 1, in Figure 3.3.

Fig. 3.5: Build and measurement layout schematic for different experimental cases
For all tests, the substrate and build material are matched. For Cases 1, 2, 3, and 4, the LPBF machine used is the EOSINT M 280 AM machine. The EOS M280 AM machine uses a 4LR-400-SM-EOS laser which operates at a wavelength of 1060-1100 nm with a power of 280W. Material specific default EOS processing parameters are used in Cases 1, 2, 3, and 4. For Cases 1 and 3 (Ti-6Al-4V), a laser power of 280 W is used with a laser scan speed of 1200 mm/s, a layer thickness of 30 µm, and a hatch spacing of 0.14 mm. For Cases 2 and 4 (Inconel® 718), a laser power of 280 W is used with a laser scan speed of 960 mm/s, a layer thickness of 40µm, and a hatch spacing of 0.11 mm. For Case 5, the Renishaw AM250 LPBF machine is used. The Renishaw AM 250 uses a 50 ms pulsed ytterbium fiber laser with an approximate wavelength of 1060 ±10 nm. Case 5 is
made with a laser power of 188 W and a laser scan speed of 1000 mm/s, a layer thickness of 30µm, and a hatch spacing of 0.10 mm. A more thorough comparison between the machines can be found in [76]. Differences in laser power for Cases 1 and 5 are tempered by the differences in laser scan speed (1200 mm/s for EOS and 1000 mm/s for Renishaw) and hatch spacing (0.14 mm for EOS and 0.10 for Renishaw). The parameter settings and build dimensions for all cases are summarized in Table 4.1.

Table 3.1: Description of experimental cases

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ti-6Al-4V</td>
<td>Inconel® 718</td>
<td>Ti-6Al-4V</td>
<td>Inconel® 718</td>
<td>Ti-6Al-4V</td>
</tr>
<tr>
<td>Build Area-XY (mm²)</td>
<td>6.35×6.35</td>
<td>6.35×6.35</td>
<td>31.8×31.8</td>
<td>31.8×31.8</td>
<td>6.35×6.35</td>
</tr>
<tr>
<td>Build Height-Z (mm)</td>
<td>1.5</td>
<td>1.5</td>
<td>0.24</td>
<td>0.24</td>
<td>1.5</td>
</tr>
<tr>
<td>Layer Thickness (µm)</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Laser Speed (mm/s)</td>
<td>1200</td>
<td>960</td>
<td>1200</td>
<td>960</td>
<td>1000</td>
</tr>
<tr>
<td>Hatch Rotation (deg)</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>Hatch Spacing (mm)</td>
<td>0.14</td>
<td>0.11</td>
<td>0.14</td>
<td>0.11</td>
<td>0.10</td>
</tr>
<tr>
<td>AM Machine used</td>
<td>EOS</td>
<td>EOS</td>
<td>EOS</td>
<td>EOS</td>
<td>Renishaw</td>
</tr>
</tbody>
</table>
3.4 Results and Discussion

3.4.1 Comparison of Ti-6Al-4V and Inconel® 718 Builds

A sample distortion cycle is shown in Figure 3.7. Initially, the substrate is static, this is the portion of time that the powder recoater mechanism is operating, shown in grey and labeled as powder spread. Then the laser selectively melts the powder according CAD file slice for that layer. The laser heats the top of build and substrate causing it to expand. At this point, the top of the substrate is hotter than the bottom, this results in the substrate bowing up. This is labeled as the laser melting portion of the build. Once the laser scan is complete, the melted material begins to cool and solidify. As the material cools, the deposited material contracts more than the solid material beneath it as a result of its higher temperature causing it to pull inward on the substrate. This causes the substrate to bow down, marked as the cooling region. In Figure 3.7, the powder spread region is marked by the grey region of the plot, the laser melting region is marked in red, and the blue region denotes the cooling region.
Distortion results for Case 1 and Case 2 are shown in Figure 3.8. Final distortion measurements show that Case 2 builds 0.38 mm (80.9%) more distortion than Case 1. The decreased amount of distortion is likely a result of the previously referenced phase transformation mechanism in Ti-6Al-4V [36, 70, 71].

Fig. 3.7: Schematic demonstrating the distortion evolution process with build phases (Regions: Grey - Powder spread, Red- Laser melting, and Blue - Cooling)
Fig. 3.8: Comparison of distortion in the Z direction for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) using a 0.82mm thick substrate.

Fig. 3.9: Comparison of distortion in the Z direction for the early layers of Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) using a 0.82mm thick substrate.
In LPBF, the laser’s penetration depth is greater than the current powder layer thickness [77]. Therefore, as the subsequent layer is scanned, previously solidified material can be reheated to the temperature where phase transformation can occur, 700°C for Ti-6Al-4V. This effect is clear when comparing the distortion of the early layers of Case 1 and Case 2. In the first layer, Case 2 reaches a maximum of 0.64 mm of distortion as compared to Case 1 which reaches a maximum of 0.22 mm. Figure 3.9 highlights the first layers of the build process. For Case 2 (Inconel®718), distortion increases in each layer. However, for Case 1 (Ti-6Al-4V), the magnitude of distortion decreases from layer 1 to layer 3. This may be due to the reduction of plastic strain due to phase transformation shown in [36].

Temperature measurements shown in Figure 3.10 show the temperature at the measurement location for Case 1 and Case 2. As temperature measurements are made in the far field from the build area and the underside of the substrate, they cannot be used to provide information about the build temperatures. Instead, temperature measurements made as part of this study are used to demonstrate when the part has reached thermal saturation as the measured temperature plateaus. For Case 1, the part is reaches thermal saturation within the first 3 layers, this can be better seen in Figure 3.11. For Case 2 (Inconel®718), temperature measurements begin to plateau much later in the build. Experimental measurements for Case 1 show that the distortion relaxation coincides with the the thermal saturation of the part between the third and fourth layer \((t=\text{approximately } 75 \text{ s})\), but further analysis and modeling is required to determine causality between these measurements.
Fig. 3.10: Comparison of temperature measurements for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) built using a 0.82mm thick substrate.

Fig. 3.11: Comparison of temperature measurements for the early layers of Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718) built using a 0.82mm thick substrate.
As the build progresses, the rate of distortion accumulation decreases for both Case 1 and 2. For these builds, distortion in the negative Z direction results in an increased powder layer thickness and more material being added to the part. This effect is confirmed by comparing measurements for Case 1 and Case 2 in Table 3.2. Measurements therein show that the excess build height in the part is within 2.5% of measurements of the final distortion measured. Therefore, as the substrate distortion increases through the build process there is an increased amount of material under the layer that is currently being processed. This excess material inhibits further increases in distortion. Post-build measurements of the x and y dimensions of the build show significant contraction of the XY cross-sectional area as compared with pre-defined CAD geometry, 4.5% for Case 1 (Ti-6Al-4V) and 3.3% for Case 2 (Inconel® 718).

Table 3.2: Post-process measurements for Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718)

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ti-6Al-4V</td>
<td>Inconel® 718</td>
</tr>
<tr>
<td>CAD Build Dimensions (mm)</td>
<td>6.35×6.35×1.5</td>
<td>6.35×6.35×1.5</td>
</tr>
<tr>
<td>Final Build Dimensions (mm)</td>
<td>6.20×6.21×1.96</td>
<td>6.25×6.24×2.33</td>
</tr>
<tr>
<td>Excess Build Height (mm)</td>
<td>0.46</td>
<td>0.83</td>
</tr>
<tr>
<td>Final Distortion Measured in situ (mm)</td>
<td>0.47</td>
<td>0.85</td>
</tr>
</tbody>
</table>
Distortion results from Cases 3 (Ti-6Al-4-V) and Case 4 (Inconel® 718) are shown in Figure 3.12. Distortion results for Cases 3 and 4 are consistent with that of Cases 1 and 2, with Case 4 (Inconel® 718) distorting more than Case 3 (Ti-6Al-4V). For these cases, Case 4 (Inconel® 718) distorts 0.36 mm (54%) more than Case 3 (Ti-6Al-4V). Distortion relaxation possibly resulting from phase transformation is less apparent in Case 3 than in Case 1 which are both built using Ti-6Al-4V. However, Case 3 (Ti-6Al-4V) does show reduced distortion accumulation in early layers when compared with Case 4 (Inconel® 718).

Fig. 3.12: Comparison of distortion in the Z direction for Case 3 (Ti-6Al-4V) and Case 4 (Inconel® 718) built using a 3.20mm thick substrate
Temperature measurements for Cases 3 (Ti-6Al-4V) and 4 (Inconel® 718), shown in Figure 3.13, show dissimilar trends as compared with their smaller build area counterparts (Case 1 (Ti-6Al-4V) and Case 2 (Inconel® 718)) shown in Figure 3.10. For the smaller build areas, the temperature measurements for Case 1 (Ti-6Al-4V) plateau whereas for Case 2 (Inconel® 718), they continually increase. The different thermal responses of Cases 3 (Ti-6Al-4V) and 4 (Inconel® 718) is likely a result of the tenfold increase in scan time as compared with Case 1 and Case 2. The increased scan time combined with the same powder spread time from Cases 1 (Ti-6Al-4V) and 2 (Inconel® 718) results in a higher temperature for thermal saturation. For these cases, neither case reaches thermal saturation.
Summary of distortion measurements can be found in Table 3.3. Measurements of excess build height and final part distortion for Cases 3 and 4, shown in Table 3.3, are consistent with results from Cases 1 (Ti-6Al-4V) and 2 (Inconel® 718). Final build measurements of the XY cross-sectional area for Cases 3 and 4 show that contraction is decreased for these part geometries. Percent reduced area as compared with the CAD model is 2.5% for Case 3 (Ti-6Al-4V) and 1.6% for Case 4 (Inconel® 718).

Table 3.3: Post-process measurements for Case 3 (Ti-6Al-4V) and Case 4 (Inconel® 718)

<table>
<thead>
<tr>
<th>Case Number</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ti-6Al-4V</td>
<td>Inconel® 718</td>
</tr>
<tr>
<td>CAD Build Dimensions (mm)</td>
<td>31.8×31.8×0.24</td>
<td>31.8×31.8×0.24</td>
</tr>
<tr>
<td>Final Build Dimensions (mm)</td>
<td>31.4×31.4×4.05</td>
<td>31.5×31.6×4.15</td>
</tr>
<tr>
<td>Excess Build Height (mm)</td>
<td>0.61</td>
<td>0.96</td>
</tr>
<tr>
<td>Final Distortion Measured In Situ (mm)</td>
<td>0.67</td>
<td>1.03</td>
</tr>
</tbody>
</table>
3.4.2 Comparison Between EOS M280 and Renishaw AM 250 Laser Powder Bed Fusion Machines

Distortion measurements for Case 1 (Ti-6Al-4V built using an EOS M280), and Case 5 (Ti-6Al-4V built using a Renishaw AM 250) can be found in Figure 3.14. The magnitude of distortion is 11% higher for Case 5 (Renishaw AM 250) as compared with Case 1 (EOS M280). As a result of using default machine operating conditions, processing parameters for both cases are different. One major difference between the two machines is the pulsed laser used in the Renishaw AM250 machine as compared with the continuous laser used in the EOS M280 machine. Pulse lasers have been shown to increase distortion and residual stress for alternate methods of laser melting [74,78]; so, it is likely that this effect would also occur in LPBF.
Fig. 3.14: Comparison of distortion in the Z direction for Case 1 (EOS M280) and Case 5 (Renishaw AM50) built using a 0.82 mm substrate

Fig. 3.15: Comparison of temperature measurements for Case 1 (EOS M280) and Case 5 (Renishaw AM50) built using a 0.82 mm substrate
Temperature measurements, shown in Figure 3.15, are affected both by the heating affects of the laser and the effects of the powder spread mechanism. Heat input per layer for Case 1 is 1.67 J/mm$^2$ for Case 1 (EOS M280) and 1.88 J/mm$^2$ for Case 5 (Renishaw AM250). Considering the differences in scan speed, power and hatch spacing the resultant power per mm$^2$ is 6.96 W/mm$^2$ for Case 1 (EOS M280) and 4.70 W/mm$^2$ for Case 5 (Renishaw AM250). However, the average time for the powder spread mechanism is 10.5 seconds for Case 1 (EOS M280) and 9.3 for Case 5 (Renishaw AM250), which results in a higher thermal saturation point for Case 5.

As a result of the higher linear heat input for Case 1 (EOS M280), the temperature in the early layers increases faster than that of Case 5 (Renishaw AM250). Higher local temperatures increase the portion of the material that is above the critical temperature for phase transformation in Ti-6Al-4V (700°C). Where it has been shown before that Case 1 demonstrates a relaxation of distortion in the early layers, there is no such effect for Case 5 (Renishaw AM250). Early layers of distortion for Case 5 (Renishaw AM250), shown in Figure 3.16, have a consistent increase in distortion in each layer as compared with relaxed distortion in Case 1 (EOS M280). Reviewing temperature measurements over the same magnified time range, see Figure 3.17, the part from Case 1 (EOS M280) heats more in each layer and is faster to reach its thermal saturation point.
Fig. 3.16: Comparison of distortion in the Z direction in the early layers using Ti-6Al-4V for Case 1 (EOS M280) and Case 5 (Renishaw AM250) built using a 0.82 mm substrate.
Fig. 3.17: Comparison of temperature measurements in the early layers using Ti-6Al-4V for Case 1 (EOS M280) and Case 5 (Renishaw AM250) built using a 0.82 mm substrate

Final build measurements for Cases 1 (EOS M280) and 5 (Renishaw AM250) are shown in Table 3.4. Note in the final build dimensions for these cases, that for Case 1 (EOS M280), the XY cross-sectional build area is 4.5% smaller than what is prescribed by the CAD file, but for Case 5 (Renishaw AM250) the XY cross-sectional build area is only 0.3% smaller that the predefined geometry. While Case 5 (Renishaw AM250) did distort 10.6% more than Case 1 (EOS M280), the improved XY cross-sectional accuracy for Case 5 (Renishaw AM250) must also be considered. In regular production, it is unlikely that a substrate this thin (0.82 mm) would be used for LPBF, depositions on thin geometries aligned in the XY plane may exhibit similar distortion as was shown in these experiments.
Determining whether contraction in XY cross-sectional area or reduced distortion in the Z axis is preferable is most likely case specific, however with further testing a balance may be found between the two.

Table 3.4: Post-process measurements of Case 1 (EOS M280) and Case 5 (Renishaw AM250)

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder Bed Machine</td>
<td>EOS M280</td>
<td>Renishaw AM250</td>
</tr>
<tr>
<td>CAD Build Dimensions (mm)</td>
<td>6.35×6.35×1.5</td>
<td>6.35×6.35×1.5</td>
</tr>
<tr>
<td>Final Build Dimensions (mm)</td>
<td>6.20×6.21×1.96</td>
<td>6.34×6.34×2.94</td>
</tr>
<tr>
<td>Excess Build Height (mm)</td>
<td>0.46</td>
<td>0.58</td>
</tr>
<tr>
<td>Final Distortion Measured In Situ (mm)</td>
<td>0.47</td>
<td>0.52</td>
</tr>
</tbody>
</table>

3.5 Conclusion

The mitigation of stress and distortion for laser powder bed fusion based additive manufacturing requires an understanding of the distortion accumulation process. Before a mitigation strategy can be recommended for a particular material, geometry, and machine it is necessary to understand how process parameters affect the build process and highlight
distortion evolution effects. Several experiments were completed to explore how changing these will affect the distortion evolution throughout the build process as well as final build distortion. Experiments included comparisons changes in of build geometry, material and LPBF machine used for manufacture of parts. Conclusions drawn from these studies are as follows:

- Inconel® 718 parts distort more than Ti-6Al-4V for the same geometry. For the small build area, Case 2 (Inconel® 718) distorts 80.9% more than Case 1 (Ti-6Al-4V). For the larger build area, Case 4 (Inconel® 718) distorts 53.7% than Case 3 (Ti-6Al-4V).

- The phase transformation induced stress relaxation inherent in Ti-6Al-4V previously demonstrated for alternate methods of additive manufacturing was demonstrated in situ for LPBF. The phase transformation for these cases results in a decrease in measured distortion when compared with identical build geometries built using Inconel® 718, which does not exhibit any stress relaxation mechanism. For Case 1 (Ti-6Al-4V), the magnitude of distortion is decreased in early layers when subjected to heating from subsequent layers.

- The part made in the Renishaw AM250 machine distorted 10.6% more than the part made in the EOS M280 LPBF machine. However, when comparing final cross-sectional area the Renishaw AM250 matched more closely with the CAD geometry (0.3% smaller) than the part made in the EOS M280 machine (4.5% smaller).
The results presented in this study demonstrate a contribution to the powder bed additive manufacturing field in the form of in situ experimental results that help define the LPBF build process and provide necessary validation results for future FE models.

3.6 Acknowledgments

Laboratory activities conducted during this research were conducted at the Center for Innovative Materials Processing through Direct Digital Deposition at Penn State. The authors would like to thank Moog Inc. for help in planning design and execution of experiments for this work. This material is based on research sponsored by Air Force Research Laboratory under agreement number FA8650-12-2-7230 and by the Commonwealth of Pennsylvania, acting through the Department of Community and Economic Development, under Contract Number C000053981. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. Any opinions, views, findings, recommendations, and conclusions contained herein are those of the author(s) and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Research Laboratory, the U.S. Government, the Commonwealth of Pennsylvania, Carnegie Mellon University, or Lehigh University. The authors would like to thank Schlumberger-Doll Research for their support of this effort. Any opinions, findings, conclusions, and/or recommendations in this paper are those of the authors and do not necessarily reflect the views of Schlumberger-Doll Research or its employees.
Chapter 4

Experimental Validation of Finite Element Modeling for Laser Powder Bed Fusion Deformation

4.1 Abstract

Experimental measurements are a critical component of model development, as they are needed to validate the accuracy of the model predictions. Currently, there is a deficiency in the availability of experimental data for laser powder bed fusion made parts. Here, two experimental builds of cylindrical geometry, one using a rotating scan pattern and the other using a constant scan pattern, are designed to provide post-build distortion measurements. Measurements are made using a coordinate-measuring machine providing distortion profiles along the height of the part at four separate locations. Measurements show that for these cylindrical thin wall builds, there is no discernable effect on distortion from using differing scan patterns. CUBES® finite element modeling software is used to model each of the experimental builds. The simulation results show good agreement with experimental measurements of post-build deformation, with an averaged percent error of 12%. The simulated results are used to study stress and distortion evolution during the

1Under Review at the journal Additive Manufacturing
build process. Internal stresses calculated by the model throughout the part are used in explaining the final part distortion. The combination of experimental and simulation results from this study show that the distortion of the top layer is relatively small (less than 30%) throughout the duration of the build process compared to the peak distortion, which occurs several layers below the most recently deposited layer. For these geometries once the part reaches a sufficient height, the peak distortion value does not change.

4.2 Introduction

Recent developments in additive manufacturing (AM) allow for the rapid production of end-use parts without the need for significant post-build machining. In particular, the accuracy attainable by laser powder bed fusion (LPBF) AM allows for parts to be built with complex interior geometry previously unattainable by traditional manufacturing means. However, residual stresses caused by localized thermal gradients in the parts often result in build failures. Build failures include: delamination of layers, support structure fracture, part interference with the recoating mechanism, high levels of post-build distortion, voids in solid material, and lack of fusion of deposited material [31, 50, 51]. In order to mitigate the several types of failure associated with high levels of material deformation, an improved understanding of how deformation and residual stress accumulate in AM parts is needed.

A variety of LPBF experiments have been performed studying the effect of changing processing parameters including scan patterns, laser speed, laser power, and melt pool size previously discussed in Chapters 2 and 3. Much of the experimental research is focused
on the micro-scale, single lines and individual layers. Pohl et al. [48] varied laser scan pattern and speed for a single layer and used post-process experimental deflection results to compare and identify the best build parameters. Work shown by Kempen et al. [52] utilizes a new technique for in situ melt pool characterization. By analyzing the melt pool in situ, ideal processing parameters are selected by performing several single track tests. While tests like these are useful in determining processing parameters required to achieve fully dense and fully fused material, they do not address geometry dependent structural stresses that build up in actual parts.

While experiments may be informative to the LPBF build process, when extended to the larger scale this type of parametric analysis proves to be expensive. In these cases, simulation can be used to identify ideal parameters to be used in LPBF. Zhang et al. [79] performed an analysis on processing parameters for the LPBF build process. The study focused on a W-Ni-Fe powder bed build where a model was used to determine processing parameters required to reach a user specified melt pool depth. Another study performed by Dai et al. [62] used simulations to predict melt pool size based off of an input laser energy density. The work focused heavily on measuring the size of the melt pool and determined that the melt pool dimensions are on the order of hundreds of microns for LPBF. These studies provide examples of how modeling can be used in the setup stages of LPBF to identify processing parameters for a specific build process without the need for expensive experiments.
Modeling of additive manufacturing has proven to be successful in improving the understanding of the distortion accumulated during the AM process and guiding the design process to reduce build failures [10, 27, 36, 41, 43, 45, 52, 58, 61, 80]. Denlinger et al. [81] provides an example of the utility that FE modeling can have in the prevention part distortion. Similar models are scarce in the powder bed field. Most models that are available are limited to simulating small build volumes [58], melt pool dynamics [62] or have limited their analysis to the thermal side of the LPBF process [43, 58, 79].

The aforementioned models are limited in implementation with powder bed AM systems in that they are too computationally expensive for application in full part-scale modeling of LPBF. Mesh refinement studies performed show that element size must be at least the size of the melt pool radius or temperature will not converge [45]. For general purpose FE software (e.g., ANSYS, Abaqus) at least four elements are required per heat source radius [58]. Therefore, models that are applicable to alternate AM processes, (e.g., Directed Energy Deposition) are not feasible to apply to powder bed AM processes as the heat source is approximately 10 times smaller for LPBF. This results in a minimum 1000 fold increase in elements to capture a similar volume of material. Currently, there are two known available software packages that are capable of modeling part-scale LPBF: (1) Diablo [61] and (2) CUBES®. To accurately model part-scale LPBF, special consideration must be made to include the complex inter-layer effects, resulting from the complex thermal history of the parts, (Chapter 2). For that reason, Cubes® is used, as it allows for accurate modeling of inter-layer effects.
Many studies focus on the micro-scale (single tracks or layers) of the LPBF process. While the smaller scale studies are necessary in defining the mechanics of LPBF, understanding how a larger part distorts as a result of the build process is an important step in build failure mitigation for LPBF. In contrast to the abundance of studies focusing on the melt pool, process parameters and microstructure, few have published final build geometry of LPBF made parts. Here, two experimental builds of a simple cylindrical geometry with differing scan patterns are deposited to measure final build geometry and distortion profiles for parts made with LPBF AM. In addition to experimental analysis, a finite element (FE) model is experimentally validated and applied. The use of modeling software for this work is to help further understanding of stress and distortion evolution throughout the build process. The experiment performed also provides necessary validation data for future LPBF models.

4.3 Experiment

4.3.1 Experimental Setup

Two LPBF builds are used to measure the distortion profiles of parts made using the LPBF build process. Experiments are designed with similar cross-sectional geometry with the goal of studying the effects scan pattern orientation. Parts are designed to be modeled to allow for further analysis on the evolution of stress and distortion. By reducing
the complexity of the part, analysis is made easier as part geometries are constant along the height of the part.

4.3.1.1 Description of Experimental Builds

Build dimensions and locations are defined by user created computer aided design (CAD) files. Builds are completed using interchangeable substrates. Interchangeable substrates allow builds to be removed from the LPBF machine without requiring post-build machining which will affect final build geometries. Substrates are constrained from underneath using restraining bolts that thread into holes on substrates, thereby restricting motion of the substrate without impacting the recoater mechanism.

Figure 4.1 is a schematic of build geometry and substrate for Case 1 and Case 2. The substrate dimensions are 88.9 mm × 38.1 mm × 3.18mm in each case. Both cases are cylindrical builds with an outer diameter of 15.88 mm and a cylinder wall thickness of 1.59 mm. As a result of a machine failure during production build heights are 6.16 mm and 12.7 mm for Case 1 and Case 2, respectively. While the difference in part height prevents direct comparisons between the two cases, each case can still be analyzed as the manufacturing worked properly until failure. Figure 4.2 shows the fully built material for Cases 1 and 2 with their substrates. In addition to differences in part height, Case 1 is built with the machine default rotating laser scan pattern and Case 2 is built with a constant scan pattern parallel with the Y axis. The rotating versus constant scan pattern are used to determine how alteration of this build parameter affects final build geometry. A schematic
demonstrating a rotating versus constant scan pattern is shown in Figure 4.3. Descriptions of Case 1 and 2 processing parameters are summarized in Table 4.1.

Fig. 4.1: Schematic of the both deposition and the substrate for: (a)-Case 1 (rotating scan pattern) (b)-Case 2 (constant scan pattern)
Fig. 4.2: Completed build with substrate for: (a)-Case 1 (rotating scan pattern) (b)-Case 2 (constant scan pattern)
The substrate and powder materials are both Inconel® 718. The average powder diameter is 30.4 ±7/22 μm. Inconel® 718 is used as it is a common superalloy used in AM across across several industries [1–3, 82, 83]. Both cases are built using the EOS M280 LPBF machine. The EOSINT M280 machine uses a 4LR-400-SM-EOS laser that operates at a wavelength of 1060-1100 nm with a power of 280W. EOS default processing parameters for Inconel® 718 include a layer thickness of 40 μm, a hatch spacing of 110 μm, a laser travel speed of 960 mm/s, and a laser power of 280 W.
Table 4.1: Description of Experimental Cases

<table>
<thead>
<tr>
<th>Case Number</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Inconel®718</td>
<td>Inconel®718</td>
</tr>
<tr>
<td>Layer Thickness $\mu$m</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Laser Speed (mm/s)</td>
<td>960</td>
<td>960</td>
</tr>
<tr>
<td>Hatch Spacing (mm)</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Rotating Scan Pattern</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

4.3.1.2 Description of Measurement Equipment

Post-process measurements of the final build geometry are performed to quantify final distortion in each of the cases. A Core® RS-50 coordinate-measuring machine (CMM) is used to measure the outside walls of each cylinder at 4 separate XY positions along the height of the parts for Case 1 and 2. The CMM uses a positive contact probe to measure the distortion profile along the height of the part. Measurement locations are shown in the schematic in Figure 4.4. Measurement locations are labeled as $+X$, $+Y$, $-X$, and $-Y$, which correspond to the center of the build, these labels will be used when comparing and contrasting results. Measurements are made approximately every 0.05 mm along the height of the part. Measurements at the base of the part, lower than approximately $z=1.5$ mm, were not captured due to the size of the measurement probe used. A recent calibration,
completed in accordance ASME B89.1, Sections 5.3, 5.4.3, 5.5.2, and 5.5.4, shows an measurement accuracy of ±0.0044 mm over 1200 mm, ±0.0032 mm over 1000 mm, and ±0.0020 mm over 750 mm in the x, y, and z direction respectively.

![Schematic of CMM measurement locations for Case 1 and 2](image)

Fig. 4.4: Schematic of CMM measurement locations for Case 1 and 2

### 4.3.2 Experimental Results

Figure 4.5(a) shows the experimental measurements for both Case 1 and Case 2 along the positive X measurement location (see Figure 4.4). For both cases, oscillation in the distortion measurements is seen along the height of the part. Given the previously stated accuracy of the CMM machine, this is likely an effect of high surface roughness, which is common for metal powder based AM [84,85]. The distortion measurement for Case 1 at the +X location distortion is nearly parabolic, with magnitude of distortion
reaching a peak (0.10 mm) at only a single height (2.86 mm), whereas the distortion profile for Case 2 (constant scan pattern) has a nearly constant magnitude of distortion (0.92 mm) along much of the part height (from approximately 2 mm to 10 mm) when excluding oscillation due to surface roughness. Figure 4.5(b) shows measurements at the +Y measurement location. Consistent distortion shape profiles are seen for both Case 1 (rotating scan pattern) and Case 2 (constant scan pattern), with surface roughness affecting the measurements for Case 1 (rotating scan pattern) between a part height of 2 mm and 4 mm. Measurements of the -X location are shown in Figure 4.5(c). Similar shape profiles are again present for both Case 1 (rotating scan pattern) and Case 2 (constant scan pattern) as with Figures 4.5(a) and 4.5(b). Measurements of the -Y measurement location, shown in Figure 4.5(d), compare well with the other measurement locations with similar magnitude and shape for both cases. For both cases and each measurement location, the part distorts inward toward the center line of the cylindrical geometry.
Fig. 4.5: Distortion measurement results along the four measurement locations for both Case 1 (rotating scan pattern) and Case 2 (constant scan pattern)

Distortion values were compared for each of the four measurement locations at several heights along the part for each case. At each height, a mean value of distortion is calculated, the averaged magnitude of distortion for each of the four measurement locations, and a percent deviation from this mean is calculated for each measurement location, to
identify any trends in distortion profiles that may align with either the X or Y directions. These measurements are located in Table 4.2 and Table 4.3 for Case 1 (rotating scan pattern) and Case 2 (constant scan pattern) respectively. To account for surface roughness, measurements at specified heights are averaged with the 5 measurement below and above selected height.

Table 4.2: Case 1 (rotating scan pattern) peak distortion comparison by percent deviation with experimental measurements

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Mean Distortion (mm)</th>
<th>Positive X (%)</th>
<th>Positive Y (%)</th>
<th>Negative X (%)</th>
<th>Negative Y (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z= 2.0</td>
<td>0.079</td>
<td>1.3</td>
<td>2.3</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Z= 3.0</td>
<td>0.086</td>
<td>13.6</td>
<td>14.8</td>
<td>4.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Z= 4.0</td>
<td>0.083</td>
<td>1.5</td>
<td>6.3</td>
<td>1.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Z= 5.0</td>
<td>0.072</td>
<td>1.8</td>
<td>4.3</td>
<td>0.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Z= 5.5</td>
<td>0.063</td>
<td>0.6</td>
<td>0.7</td>
<td>5.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Table 4.3: Case 2 (constant scan pattern) peak distortion comparison by percent deviation with experimental measurements

<table>
<thead>
<tr>
<th>Part Height (mm)</th>
<th>Mean Distortion Magnitude (mm)</th>
<th>Positive X Position (%)</th>
<th>Positive Y Position (%)</th>
<th>Negative X Position (%)</th>
<th>Negative Y Position (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z= 2.0</td>
<td>0.087</td>
<td>1.7</td>
<td>1.6</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Z= 4.0</td>
<td>0.098</td>
<td>12.7</td>
<td>7.8</td>
<td>3.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Z= 6.0</td>
<td>0.099</td>
<td>10.7</td>
<td>8.8</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Z= 8.0</td>
<td>0.103</td>
<td>1.4</td>
<td>2.3</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Z= 10.0</td>
<td>0.102</td>
<td>6.8</td>
<td>1.5</td>
<td>1.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Z= 12.0</td>
<td>0.082</td>
<td>13.3</td>
<td>1.8</td>
<td>1.0</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Direct comparison cannot be made between Case 1 and Case 2 as a result of their differing build heights, but comparisons can be made between the different measurement locations within each case. Tables 4.2 and 4.3 show that for both Cases 1 and 2 distortion measurements are consistent (under 15% difference) for each direction with no increased distortion trend aligned with either the X or Y directions. For Case 1, a rotating scan pattern is used, so it is expected that distortion profiles would be independent of measurement location. For Case 2, all laser scans are aligned with the Y-axis (Figure 4.3) so an asymmetry is expected for the distortion profiles. In particular, it is expected that
the Y distortion profiles (longitudinal) would be larger than the X (transverse) distortion profiles [31]; however, no trend is found in the distortion profiles for Case 2 (constant scan pattern). Instead, large deviations found in any measurement location seem to be the result of localized defects, identified by large deviations from the mean distortion profile at only a single heights with no trend continuing along the entire part height.

For each measurement location, distortion profiles for Case 2 (constant scan pattern) plateau at a part height of 3 mm, whereas the distortion profile for Case 1 (rotating scan pattern) reaches a peak distortion at one height resulting in a shape that is most nearly parabolic and where no plateau is reached. This is a result of their relative build heights where Case 1 is 6.16 mm tall and Case 2 is approximately 12.6 mm tall. For the geometry used in these experiments, at a height of 4mm, the rate at which distortion increases with height levels off until near the top of the part at approximately 10 mm. At low build heights the deposited material is constrained by the substrate thereby reducing the amount of distortion possible. As the part increases in height during the build process, the constraining effects of the substrate are minimized, and the part can distort freely. Distortion for these geometries is caused by the melted material of the current layer solidifying and compressing the material below it. For both cases, material near the top of the part distortion decreases rapidly as there are not enough layers above this point to compress the material and cause significant distortion. To further examine these effects, an FE model is used to provide analysis and to help understand the distortion evolution throughout the build process.
4.4 Powder Bed Fusion Simulation

The thermal and mechanical histories are determined by performing a three-dimensional transient thermal analysis and a three-dimensional quasi-static incremental analysis, respectively. The thermal and mechanical analyses are performed independently and are weakly coupled, meaning that the mechanical response has no effect on the thermal history of the workpiece [86].

4.4.1 Thermal Analysis

The governing heat transfer energy balance is written as:

\[ \rho C_p \frac{dT}{dt} = -\nabla \cdot q(r, t) + Q(r, t) \]  

(4.1)

where \( \rho \) is the material density, \( C_p \) is the temperature dependent specific heat capacity, \( T \) is the temperature, \( t \) is the time, \( Q \) is the volumetric internal heat generation rate, \( x \) is the relative reference coordinate, and \( q \) is the heat flux vector. The Fourier heat flux constitutive relation is:

\[ q = -k\nabla T \]

(4.2)

where \( k \) is the temperature dependent thermal conductivity.

Thermal radiation \( q_{rad} \) is calculated using the Stefan-Boltzmann law:
\[ q_{rad} = \varepsilon \sigma (T_s^4 - T_\infty^4) \]  

(4.3)

where \( \varepsilon \) is the surface emissivity, \( \sigma \) is the Stefan-Boltzmann constant, and \( T_s \) is the surface temperature of the workpiece.

Newton's law of cooling calculates convective heat loss \( q_{\text{conv}} \):

\[ q_{\text{conv}} = h(T_s - T_\infty) \]  

(4.4)

where \( h \) is the convective heat transfer coefficient.

### 4.4.2 Mechanical Analysis

A quasi-static mechanical analysis is performed to calculate the mechanical response of the workpiece. The results of the thermal analysis are imported as a thermal load into the mechanical analysis. The governing stress equilibrium equation is:

\[ \nabla \cdot \sigma = 0 \]  

(4.5)

where \( \sigma \) is the stress. The mechanical constitutive law is:

\[ \sigma = C \varepsilon \]  

(4.6)
Total strain $\mathbf{e}$, assuming small deformation thermo-elasto-plasticity, is decomposed as:

$$\mathbf{e} = \mathbf{e}_e + \mathbf{e}_p + \mathbf{e}_T \quad (4.7)$$

where $\mathbf{C}$ is the fourth-order material stiffness tensor, and $\mathbf{e}_e$, $\mathbf{e}_p$, $\mathbf{e}_T$, and $\mathbf{e}_t$ are the elastic, plastic, and thermal strain, respectively. The thermal strain is computed as:

$$\mathbf{e}_T = \mathbf{e}_T \mathbf{j} \quad (4.8)$$

$$\mathbf{e}_T = \alpha(T - T_{ref}) \quad (4.9)$$

$$\mathbf{j} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}^T \quad (4.10)$$

where $\alpha$ is the thermal expansion coefficient and $T_{ref}$ is reference temperature. The plastic strain is computed by enforcing the von Mises yield criterion and the Prandtl-Reuss flow rule:

$$f = \sigma_m - \sigma_y(\mathbf{e}_q, T) \leq 0 \quad (4.11)$$

$$\dot{\mathbf{e}}_p = \dot{\mathbf{e}}_q \mathbf{a} \quad (4.12)$$

$$\mathbf{a} = \left( \frac{\partial f}{\partial \sigma} \right)^T \quad (4.13)$$
where \( f \) is the yield function, \( \sigma_m \) is Mises’ stress, \( \sigma_Y \) yield stress, \( \epsilon_q \) is the equivalent plastic strain, and \( \mathbf{a} \) is the flow vector.

### 4.4.3 Numerical implementation

The thermal and mechanical analyses are performed using CUBES® (version 2.81) by Pan Computing LLC. The analyses are done in a series of time steps with the current time step taking the solution at the previous time step as the initial condition. At each time step, the discrete equilibrium equations are solved by using the Newton-Raphson method.

Table 4.4 lists the temperature dependent thermal properties for Inconel® 718. Table 4.5 list the mechanical properties of the material including the Elastic Modulus, \( E \), yield stress, \( \sigma_y \), and thermal expansion coefficient, \( \alpha \). Table 4.6 lists the as-used constant material properties and processing conditions for the analyses.

<table>
<thead>
<tr>
<th>( T [^\circ C] )</th>
<th>( k_s [W/m/\circ C] )</th>
<th>( C_p [J/kg] )</th>
<th>( \varepsilon_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>11.4</td>
<td>427</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>12.5</td>
<td>441</td>
<td>-</td>
</tr>
<tr>
<td>300</td>
<td>14.0</td>
<td>481</td>
<td>-</td>
</tr>
<tr>
<td>500</td>
<td>15.5</td>
<td>521</td>
<td>-</td>
</tr>
<tr>
<td>538</td>
<td>-</td>
<td>-</td>
<td>0.28</td>
</tr>
<tr>
<td>649</td>
<td>-</td>
<td>-</td>
<td>0.42</td>
</tr>
<tr>
<td>700</td>
<td>21.5</td>
<td>601</td>
<td>-</td>
</tr>
<tr>
<td>760</td>
<td>-</td>
<td>-</td>
<td>0.58</td>
</tr>
<tr>
<td>1350</td>
<td>31.3</td>
<td>691</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4.5: Temperature dependent mechanical properties of solid Inconel® 718 [3]

<table>
<thead>
<tr>
<th>$T$ [$^\circ$C]</th>
<th>$E$ (GPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\alpha$ ($\mu$m /m $^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>208</td>
<td>1172</td>
<td>12.8</td>
</tr>
<tr>
<td>93</td>
<td>205</td>
<td>1172</td>
<td>12.8</td>
</tr>
<tr>
<td>204</td>
<td>202</td>
<td>-</td>
<td>13.5</td>
</tr>
<tr>
<td>316</td>
<td>194</td>
<td>-</td>
<td>13.9</td>
</tr>
<tr>
<td>427</td>
<td>186</td>
<td>1089</td>
<td>14.2</td>
</tr>
<tr>
<td>538</td>
<td>179</td>
<td>1068</td>
<td>14.4</td>
</tr>
<tr>
<td>649</td>
<td>172</td>
<td>1034</td>
<td>15.1</td>
</tr>
<tr>
<td>760</td>
<td>162</td>
<td>827</td>
<td>16.1</td>
</tr>
<tr>
<td>871</td>
<td>127</td>
<td>286</td>
<td>-</td>
</tr>
<tr>
<td>954</td>
<td>17.8</td>
<td>138</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Table 4.6: As-used constant material properties and processing conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature $T_\infty$ [$^\circ$C]</td>
<td>25 [75]</td>
</tr>
<tr>
<td>Convection coefficient $h$ [W/m$^2$/°C]</td>
<td>8</td>
</tr>
<tr>
<td>Density $\rho$ [kg/m$^3$]</td>
<td>8146 [1]</td>
</tr>
<tr>
<td>Laser absorptivity $\eta$</td>
<td>0.40 [87]</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.30 [3]</td>
</tr>
</tbody>
</table>

Loose powder that goes unmelted during the deposition process is not included as part of the analysis. Conduction into the powder is modeled by applying an artificial convective boundary condition on the model. Several simulations using varying convection
coefficients $h$ were run in order to determine the sensitivity of the model to this unknown parameter. The result of these studies show that for these build geometries a 50% increase or decrease in the value of convection coefficient result in less than 1% error on final distortion results shown in Figure 4.6.

![Graph showing sensitivity of post-build distortion to FE model convection coefficient for constant scan pattern case (Case 2)](image)

Fig. 4.6: Sensitivity of post-build distortion to FE model convection coefficient for constant scan pattern case (Case 2)

Figure 4.7 shows the mesh used for the analysis. Three different mesh densities were simulated for each case to determine if the simulations were mesh independent. A mesh refinement study was completed for both temperature and distortion results, and for both
cases the mesh used for the analysis demonstrated monotonic convergence with a peak difference of distortion magnitude under 2%.

![Mesh for analysis](image)

Fig. 4.7: Mesh used for: (a)-Case 1 (rotating scan pattern) simulation (b)-Case 2 (constant scan pattern) simulation

The laser heat source $Q$ is modeled using the double ellipsoid model [88]:

$$Q = \frac{6\sqrt{3}P\eta}{abc\pi\sqrt{\pi}} e^{-\left[\frac{3x^2}{a^2} + \frac{3y^2}{b^2} + \frac{3(z+vt)^2}{c^2}\right]}$$  \hspace{1cm} (4.14)
where $\eta$ is the absorption efficiency; $x$, $y$, and $z$ are the local coordinates; $a$, $b$, and $c$ are the transverse, depth, and longitudinal dimension of the ellipsoid respectively.

4.5 Results and Discussion

4.5.1 Model Comparison To Experimental Measurements

Simulation results were extracted at the experimental measurement locations (Figure 4.4). For ease of comparison and to reduce noise from surface roughness, experimental measurements were averaged in groups of 10 with the standard deviation indicated by error bars.
Fig. 4.8: Averaged CMM measurements of post-build distortion compared against FE model results at the four measurement locations shown in Figure 4.4

A comparison between simulation results and experimental measurements for both Case 1 (rotating scan pattern) and Case 2 (constant scan pattern) can be found in Figure 4.8(a) for the positive X location. Similar comparison for the experimental measurements and simulation results for the positive Y measurement location can be found in Figure
4.8(b). Effects of surface roughness, which cannot be captured by the model, affect the comparison between the model and experiments for Case 1 in Figure 4.5(b) most notably at a height of 3 mm. Simulation results compared with experimental measurements are shown in Figure 4.8(c) for the negative X location. A significant part defect, caused by earlier described surface effects common to AM, for Case 2 at a part height of 7 mm causes a localized discrepancy, but model results match experimental results outside of this region. The comparison for Case 1 is within measurement averaged standard deviation indicated by the error bars. The comparison of the simulation results and experimental measurements for the negative Y location is shown in Figure 4.8(d). For each case, the FE model results match the experimental measurements well in both trend and magnitude.
Table 4.7: Comparison of experimental measurements and simulation results for Case 1 (Rotating scan pattern). The error is averaged at each nodal location in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by the experimental distortion measurement at each height.

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Averaged Error in FE Model Along the Height of the Part (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive X Position</td>
<td>6.2</td>
</tr>
<tr>
<td>Positive Y Position</td>
<td>10.2</td>
</tr>
<tr>
<td>Negative X Position</td>
<td>5.1</td>
</tr>
<tr>
<td>Negative Y Position</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Table 4.8: Comparison of experimental measurements and simulation results for Case 2 (Constant scan pattern). The error is averaged at each node in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by experimental distortion measurement at each height.

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Averaged Error in FE Model (Along the Height of the Part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive X Position</td>
<td>11.8</td>
</tr>
<tr>
<td>Positive Y Position</td>
<td>4.5</td>
</tr>
<tr>
<td>Negative X Position</td>
<td>7.6</td>
</tr>
<tr>
<td>Negative Y Position</td>
<td>7.6</td>
</tr>
</tbody>
</table>

For quantitative comparison between experiment and simulation, comparisons were made at each nodal position along the height of the part in the FE model. Simulation results were averaged at each nodal height along the height of the part for each measurement locations (e.g. +X,+Y,-X,-Y). Comparisons for Case 1 and Case 2 are shown in Table 4.7 and Table 4.8, respectively. On average, FE model results compare well with experimental measurements with the largest difference the +X measurement location for Case 2 (12%). Measurement locations with large percent errors correlate with previously discussed defects.
and roughness in experimental build surfaces. The CUBES solver does not calculate surface roughness; so, capturing these effects was not expected.

4.5.2 Substrate Deformation

Reviewing distortion measurements for Case 2 (constant scan pattern) for the positive and negative X measurement locations, an indentation in the distortion profile can be seen between a build height of approximately 4 mm and 8 mm. Simulations, shown in Figures 4.12 and 4.8, modeled with a rigid substrate are unable to capture this feature in the distortion profile. To further investigate, a simulation with a flexible substrate that more closely matches the boundary conditions defined in 4.1 was completed. FE model results of the distortion of the substrate in the build direction (Z) are compared against in situ experimental measurements. The measurement location for the Z distortion is found in Figure 4.9.
Measurements of distortion are made using the same differential variable reluctance transducer (DVRT) previously described in Chapters 2 and 3. A comparison of simulation results and experimental measurements of the distortion in the build direction is found in Figure 4.10. At approximately 2400 seconds, the measurement equipment lost power and stopped recording, this is denoted in Figure 4.10 by a vertical dotted line. The FE model is able to accurately predict the distortion for the duration of the measurement period. Assuming the final distortion measured in the experiment is accurate, the model result is within 0.01 mm placing it within 10% of the experimental measurement.
Fig. 4.10: Comparison of experimental and FE model results for distortion of the substrate in the build direction
Fig. 4.11: Distortion results for simulation of Case 2 (Constant Scan Pattern) with and without a flexible substrate for each of the four measurement locations shown in Figure 4.4

Results for each of the measurement directions are shown in Figure 4.11. From the results shown in Figure 4.11, it can be surmised that the localized indentation in the X measurement locations are likely caused by the flexible substrate. The effect is likely driven by the X measurement locations being aligned with the long dimension of the substrate,
which is able to deform. As the substrate buckles in the negative Z direction, it causes an indentation in the cylinder wall. This can be concluded by analyzing the Y measurement locations in Figures 4.11(b) and 4.11(b), wherein the inclusion of the flexible substrate did not change the shape of the distortion profile, instead only the magnitude of the distortion along the part height. As no indentation is observed for Case 1 (rotating scan pattern), it is also likely that the indentation is affected by part height. Inclusion of the flexible substrate in the simulation improves the accuracy as compared with experimental measurements and demonstrates another level of utility gained through FE modeling. Table 4.9 presents quantitative results demonstrated improved accuracy of the flexible simulation, using the previously described method for determining model accuracy to experimental measurements. Results shown in Table 4.9 show increased simulation accuracy in the Positive X and Negative X directions, but at a cost of accuracy in the Y directions.
Table 4.9: Comparison of experimental measurements and simulation results for Case 2 (Constant scan pattern) with and without a flexible substrate. The error is averaged at each node in the FE model along the height of the part for each measurement location (Figure 4.4). Measurements are normalized by experimental distortion measurement at each height.

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Averaged Error in FE Model Along the Height of the Part</th>
<th>Averaged Error in FE Model Along the Height of the Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Substrate (%)</td>
<td>Flexible Substrate (%)</td>
<td></td>
</tr>
<tr>
<td>Positive X Position</td>
<td>11.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Positive Y Position</td>
<td>4.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Negative X Position</td>
<td>7.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Negative Y Position</td>
<td>7.6</td>
<td>9.4</td>
</tr>
</tbody>
</table>

4.5.3 Extension of Rotating Scan Pattern Case

Due to a shortage of powder during the build process, the rotating scan pattern case was built shorter than designed. Using the previously validated model, the rotating scan pattern model was extended to its prescribed build height. The results of the extended rotating scan pattern case are shown in Figure 4.12.
Fig. 4.12: Extension of the rotating scan pattern case to full build size for the four measurement locations shown in Figure 4.4

As can be seen in Figure 4.12 previous statements regarding the minimal effect of rotating scan pattern for the thin-walled geometry is confirmed. For each of the measurement locations, the rotating scan pattern consistently distorts less than the constant scan pattern, but the difference between the two cases are on average 1-2% which is well within the models
determined accuracy. The use of the FE model to provide a comparison of a part that was not successfully built with one that built correctly highlights another potential applications for FE model usage in the furthering of LPBF AM.

4.5.4 Distortion Evolution in Time

For both cases, the final shape of the deposited cylinder flares out at the bottom where attached to the substrate, and the top where uncompressed by subsequent layers. Figure 4.13 shows the simulation prediction of the build geometry, with distortion magnified 10 times, at the halfway (Figure 4.13 (a) and (c)) and final Figure 4.13 ((b) and (d)) build time for Cases 1 and 2. The distortion magnitude for the constant scan pattern case (Case 2) indicates that at halfway through build, shown in Figure 4.13(c)), the part has already reached the peak distortion magnitude, whereas for the rotating scan pattern distortion at halfway through the build (Figure 4.13(a)) is lower than the final distortion values. The change in the profile of the part from Figure 4.13(a) to 4.13(b) and Figure 4.13(c) to 4.13(d) shows that the maximum distortion is not located at the top layer; rather, it is located at layers several layers beneath the top layer. This furthers the conclusion that for this geometry, distortion is caused by the multiple layers solidifying and compressing layers previously built. The accumulation of tensile stresses induced by the cooling and contracting of newly deposited material forces the middle area of the part into compression. For all four contour plots, distortion is a local minimum at the top layer whether halfway though the build or the finished build.
Fig. 4.13: Contour plots of distortion in mm (distortion magnified 10x) for: (a)-Case 1 (rotating scan pattern) halfway through build (b)-Case 1 (rotating scan pattern) finished build after part has cooled to ambient temperature (c)-Case 2 (constant scan pattern) halfway through build (d)-Case 2 (constant scan pattern) finished build after part has cooled to ambient temperature
Fig. 4.14: Comparison of the current part height and peak distortion height versus time for the negative X measurement location for Case 2 (constant scan pattern)

Figure 4.14 compares the distortion value of the current top layer and the maximum distortion versus time for Case 2. At time $t=4000\text{s}$, the build process is completed, and the simulation allows the part to cool back to ambient temperature ($T=25\,^\circ\text{C}$), causing the part to contract, resulting in an increase of the magnitude of the distortion profile. The importance of Figure 4.14 is to demonstrate that from extremely early in the build (approximately $t=100\text{s}$) peak distortion is not at the top layer, but instead at a lower layer. Therefore, distortion in these geometries is not a single layer effect, but instead it is the cumulative effect of multiple layers.
Fig. 4.15: Comparison of the distortion of the top layer and the peak distortion value versus time for the negative X measurement location for Case 2 (constant scan pattern)

Figure 4.15 shows the current height of the part and the height along the wall where the peak distortion is located for Case 2. Although, the location of the peak distortion continues to rise throughout the build process, it climbs slower than the height of the part.

For the majority of the build process, peak distortion is not found at the top layer, but instead at the layers below. During the build process, initially the peak distortion is located at the current layer, but once a sufficient part height is reached approximately (6.5mm), the part height where the current peak distortion is located lags behind the height of the current layer. This can be seen in Figure 4.15. Additionally, once the build progresses to approximately 2000s (build height of 6.24 mm), the value of the peak distortion plateaus. The plateau of distortion shown in Figure 4.15 shows that once a sufficient build height is
reached, peak distortion will become independent of part height. This effect determines the final shape of cylinders made in a LPBF build process which are flared out at the bottom and top of the part as the part restricted by the substrate below it and the top is relatively undistorted as there is no material above it to compress it. Results from the model give insight to distortion accumulation process and how currently added layers can affect previous layers.
Fig. 4.16: Case 2 (constant scan pattern) contour plots of Cauchy stress in MPa (distortion magnified 2.5x) for: (a)-Cauchy XX stress halfway through build halfway through build (Z=6.3 mm) (b)-Cauchy YY stress halfway through build (Z=6.3 mm) (c)-Cauchy XX stress for finished build (d)-Cauchy YY stress for finished build

Examining stress contours calculated by the model can help explain the final shape of the part. X and Y principle Cauchy stresses are shown in Figure 4.16 at various heights through the build at halfway through the build process and for the completed part. Figure 4.16 shows the bottom and top layers are in tension with high stress magnitudes. For
each of the measurement locations, the distortion is minimal at the top and bottom of the part. In the middle of the part compressive stresses dominate, reaching a maximum (approximately -1600 MPa) between a part height of 2 mm and 10 mm. Distortion reaches its peak magnitude in this region. Cauchy XX and YY stress profiles shown in Figures 4.16(c) and 4.16(d), demonstrate this transition from tension at the bottom to compression throughout much of the part height back to tension at the top of the part. The result of this is a part that is undistorted at the top and bottom and with significant distortion between those section, resulting in an hourglass-like shape.

As is shown in Figure 4.13, the built material final geometry resembles the previously described hourglass shape with distortion toward the centerline of the cylinder’s geometry for the majority of the height of the part. When comparing Cauchy XX Stress (Figures 4.16(a) with 4.16(c)) and Cauchy YY stress (Figures 4.16(b) with 4.16(d)) for the halfway completed and fully completed builds, the maximum and minimum stress values at halfway through the build are within 5% of the completed build minimum and maximum stresses. Stress calculations are consistent with previous statements that the magnitude of distortion is independent of height, once a sufficient part height is reached for this geometry. For these parts, distortion and stress are caused by the accumulation of compression effects from multiple layers.
4.6 Conclusion

Two experimental builds with a simple cylindrical geometry are manufactured in a LPBF machine, one built with a rotating scan pattern and the other with a constant scan pattern, with the goal of providing measurements of the post-build distortion. CMM measurements of distortion show that for both cases, the parts distort towards the center line of the cylinder with equal magnitude for each measurement location for both cases. Experimental measurements are compared against CUBES® FE model for validation purposes. FE model results compare well with experimental measurements made. The highest averaged percent error for any measurement location distortion profile falls within 12% of the experimental measurement. For this geometry, distortion and residual stress accumulation is caused by solidifying material in the current layer compressing previous layers causing the part to distort inwards. As a result, distortion in the current top layer typically small (less than 30% of the peak distortion) during the build process and peak distortion is typically several layers below the top layer. Stress profiles calculated using the FE model are used to further explain the distortion profile along the height of the part.

4.7 Acknowledgments

Laboratory activities conducted during this research were conducted at the Center for Innovative Materials Processing through Direct Digital Deposition at Penn State. This material is based on research sponsored by Air Force Research Laboratory under
agreement number FA8650-12-2-7230 and by the Commonwealth of Pennsylvania, acting through the Department of Community and Economic Development, under Contract Number C000053981. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. Any opinions, views, findings, recommendations, and conclusions contained herein are those of the author(s) and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Research Laboratory, the U.S. Government, the Commonwealth of Pennsylvania, Carnegie Mellon University, or Lehigh University. The authors would like to thank Schlumberger-Doll Research for their support of this effort. Any opinions, findings, conclusions, and/or recommendations in this paper are those of the authors and do not necessarily reflect the views of Schlumberger-Doll Research or its employees.
Chapter 5


5.1 Abstract

To identify the mechanical properties of laser powder bed fusion (LPBF) support structures, experimental measurements of the tensile strength are necessary. Tensile samples are designed, built and tested with to quantify mechanical properties of LPBF support structure. Measurements of block type support structure show that the tensile strength of LPBF built support structure is 30-40% of that of solid material built in the same machine and same material. CT scan images of support structure show that poor build quality in early layers of support structure are a major factor for the decrease in material strength. Poor build quality is believed to be the result of insufficient heat for fusion of support structure to solid material. Experimental measurements made as part of this study provide clear failure criteria that can be implemented to prevent failure of support structure in future builds.
5.2 Introduction

Additive manufacturing (AM) allows for the production of parts with complex geometries and internal structures that would not be feasible using traditional forms of manufacturing. Laser powder bed fusion (LPBF), a common method of AM, allows for the production of near-net shape and net shape parts. Parts made using LPBF are constructed from a series discrete 2D horizontal layers that are approximately 10-80 µm thick. As a result, components that contain overhanging geometries will often require the implementation of support structure to prevent collapse during the manufacturing process [65]. In addition to preventing failure of overhanging geometries, support structure are also implemented in conjunction with design features known to cause deformation [64]. Currently, there is limited experimental analysis identifying support structure failure criteria; as a result, support structures are often implemented in LPBF builds with inadequate information to ensure their effectiveness.

Research efforts focus on optimizing support structures in LPBF typically include: the reduction of material used, the reduction of build time, ease of removal after the build is complete, etc. [65, 66]. Kulkarni et al. [66]demonstrates different methods of support structure optimization by altering the part orientation in the machine . Optimization can include design of new support structure geometries have focusing on the reduction of material and improved powder recovery [89]. These methods can result in a reduction of material and build time, but ignore the potential effects of the minimization of support
structure on part distortion and build failure. The overall purpose of many support structure optimizations is to reduce build time and material consumed on support structure that must be removed after the build is complete.

Calignano [65] has performed experiments focusing on design parameter optimization for differing support structure designs. Experimental results from this work provide comparative analysis of different process parameters and build materials. The results from the experimental builds are organized into comparisons, providing insight to the design and optimization of support structure. In another study, experiments on several different support structures are completed comparing the ease of support structure removal from the solid part material [67]. Experimental results from both studies are qualitative and provide comparative results for specific support structure geometries and design features. A finite element (FE) model was developed by Krol et al. [68] wherein simulations of different support structures are examined and compared against one another to identify regions of high stress in the support structure. A common feature absent from all of these studies is the lack of discrete measurements of support structure mechanical properties. Without clearly defined mechanical properties to define failure criteria for support structure, optimizations cannot ensure successful builds and analysis remain qualitative.

Support structures are implemented in AM builds to restrain large-scale distortion and prevent build failures. To ensure successful builds, it is necessary to have the mechanical properties of the support structure before the build process. It has been
shown that changes in processing parameters can have a large impact on the mechanical properties of LPBF built materials [90]. By default, support structures are built using altered processing parameters than those used for solid material [65]. Many studies have been completed to quantify the post-build material properties of AM made material [90–95], but there are limited results for similar quantitative analysis for the mechanical properties of support structures [65,67].

Changes in AM processing parameters and implementation of lattice geometry are likely to result in significant changes in the mechanical properties of support structures as compared with solid material. To test this, experimental tensile samples are built in an EOS M280 LPBF machine with the goal of measuring the mechanical properties of the support structure. Tensile test specimens are designed using a common support structure geometry, block type [65,67], with varied hatch spacing to quantify tensile strength of support structure with varied material. In addition to providing quantitative analysis of mechanical properties of support structure, experimental measurements provide validation data of support structure for modeling software.

5.3 Description of Experimental Procedure

5.3.1 Design of Experimental Test Pieces

Four sets of ten tensile specimens were designed and built to test the strength of LPBF built support structures. Test samples are designed with solid material at their
bottom and top to provide grip regions for tensile tests. Tensile specimens are 25 mm × 14 mm × 2 mm, and contain block type support structure, shown in Figure 5.1(b) in the middle of the part height (part height of 11.5 - 13.5 mm) with dimensions of 2 mm × 9 mm × 1.90 mm. Dimensions of the tensile test pieces can be found Figure 5.1.

(a) Front View

(b) Top View

Fig. 5.1: Schematic of the tensile test specimens
Initially, test samples were built with the entire XY cross-section made of support structure, but test samples built with this geometry resulted in large scale distortions and impact with recoating mechanism causing the samples to collapsed during the build process. Failed builds are shown in Figure 5.2.

Fig. 5.2: Failed tensile samples that failed during the build process
Solid material is included throughout the build height, shown in Figure 5.1, to prevent build failure. Prior to machining the samples were heat treated to prevent build failure upon the removal of solid material braces. Once heat treated, tensile samples were then removed using electrical discharge machining. With the addition of solid material, it was necessary to machine tensile samples after the build process. Solid material was cut using electrical discharge machining, to remove solid material on either side of the sample to ensure that only the tensile strength of the support structure is measured. Figure 5.3 shows a close-up of a sample post machining.

![Support Structure Cut in solid material](image)

Fig. 5.3: Magnification of tensile specimen highlighting the post-build machining required to remove solid material for testing of support structure

Four separate hatch patterns were designed for the block type support structure to quantify how an increase in material in the support structure will affect tensile strength.
In Figure 5.1(b), the hatch pattern spacings are defined with x and y, which have different values for each sample type. As shown in Figure 5.1(b), the support structure is not aligned with the sample’s X or Y dimension to prevent effects from recoater interference. Figure 5.4 shows one sample from each tensile specimen type.

![Image of samples](image_url)

**Fig. 5.4:** Example of each of the 4 tensile sample types

Upon inspection, each tensile specimen appears the same, but unique internal hatch spacing for the support structure is used in each of the sample types. Sample type 1 uses the default block type support spacing (0.70 mm) as defined by Magics Version 19 (Materialize Software). Sample type 2 is built has half of the default spacing (0.35 mm) in the Y direction and the default spacing in the X direction. Sample type 3 has a hatch spacing of 0.35 mm in the X direction and the default spacing in the Y direction. Sample type 4 is
built using half of the default spacing in both the X and Y directions. Ten samples were built for each of the 4 sample types. A summary of the dimensions of each sample type is shown in Table 5.1.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x Hatch Spacing (mm)</td>
<td>0.70</td>
<td>0.70</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>y Hatch Spacing (mm)</td>
<td>0.70</td>
<td>0.35</td>
<td>0.70</td>
<td>0.35</td>
</tr>
<tr>
<td>Prescribed XY Cross-Sectional Area (mm²)</td>
<td>6.76</td>
<td>9.05</td>
<td>9.04</td>
<td>11.3</td>
</tr>
</tbody>
</table>

### 5.3.2 Processing parameters

Tensile specimens are made of Ti-6Al-4V and are built in an EOS M280 LPBF AM machine. The EOS M280 AM machine operates with a 4LR-400-SM-EOS laser with a wavelength of 1060-1100 nm. Material specific default EOS processing parameters are used for both the support structure and the solid material. Solid material is processed with a laser power of 340 W, a laser scan speed of 1250 mm/s, a layer thickness of 60 µm, and a hatch spacing of 0.12 mm. Support structures are processed with a laser power of 100 W, scan speed of 600 mm/s and a layer thickness of 60 µm. Block type supports are
constructed with single passes; so, no hatch rotation or hatch spacing parameter is denoted.

Process parameters are summarized in Table 5.2

<table>
<thead>
<tr>
<th>Material Support Structure</th>
<th>Solid Material</th>
<th>Support Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Power (W)</td>
<td>340</td>
<td>100</td>
</tr>
<tr>
<td>Layer Thickness (µm)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Laser Speed (mm/s)</td>
<td>1250</td>
<td>600</td>
</tr>
<tr>
<td>Hatch Rotation (deg)</td>
<td>67</td>
<td>NA</td>
</tr>
<tr>
<td>Hatch Spacing (mm)</td>
<td>0.12</td>
<td>NA</td>
</tr>
</tbody>
</table>

5.3.3 Measurement Procedure

Uniaxial tensile testing was performed using the 4206 Instron servo-mechanical testing frame. Samples were loaded using a tension rate of 0.1 mm/min. This corresponds to a strain rate of $8.3 \times 10^{-4}$ seconds. Digital image correlation (DIC) is used to measure the in-plane surface deformation fields during the loading of each sample. By utilizing a virtual extensometer, via the DIC analysis, an effective strain rate was measured. Measurements
made assume that distortion during the testing was focused primarily in the support structure region. Measurements of force at failure, $F_{Max}$ are made from the uniaxial tension tests. Two different stresses, $\sigma_{Conservative}$ and $\sigma_{Prescribed}$ are calculated from the measurement of $F_{Max}$ and varied areas. $F_{Max}$ describes the force at failure averaged across each of the samples tested for each sample type.

$$\sigma_{Conservative} = \frac{F_{Max}}{A_{Conservative}}$$ (5.1)

$\sigma_{Conservative}$, defined in Equation 5.1, is the measured stress calculated using the swept XY cross-sectional area ($A_{Conservative}$) of the support structure (1.9 mm × 9.0 mm).

$$\sigma_{Prescribed} = \frac{F_{Max}}{A_{Prescribed}}$$ (5.2)

Equation 5.2 shows definition of $\sigma_{Prescribed}$ which is calculated using the prescribed XY cross-sectional area of built material ($A_{Prescribed}$) in the support structure, shown in Table 5.1.

### 5.4 Results and Discussion

Measured results for the tensile tests are reported in Table 5.3. For each sample tested, the failure location is at the lower solid material and support structure interface as shown in Figure 5.5. An example stress-strain curve is shown in Figure 5.6 for each of
the four sample types. The linear response of the stress-strain curve is indicative of brittle fracture.

Table 5.3: Averaged Results for Tensile Tests

<table>
<thead>
<tr>
<th>Case</th>
<th>$F_{Max}$ (kN)</th>
<th>$\sigma_{Conservative}$ (MPa)</th>
<th>$\sigma_{Prescribed}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Type 1</td>
<td>2.82 ±0.46</td>
<td>176 ±29</td>
<td>417 ±29</td>
</tr>
<tr>
<td>Sample Type 2</td>
<td>4.17 ±0.45</td>
<td>260 ±28</td>
<td>460 ±39</td>
</tr>
<tr>
<td>Sample Type 3</td>
<td>4.76 ±0.43</td>
<td>297 ±27</td>
<td>527 ±42</td>
</tr>
<tr>
<td>Sample Type 4</td>
<td>5.61 ±0.64</td>
<td>350 ±40</td>
<td>496 ±53</td>
</tr>
</tbody>
</table>

$^1$Tensile tests performed by Dr. Allison Beese, Shipin Qin and Lourdes Bobbio
Fig. 5.5: Example tensile specimen after testing
Fig. 5.6: A representative stress versus strain curve for each sample type \(^1\)

Considering the varying stresses measured described in Equations 5.1, and 5.2, the strength of the support structure samples ranges from approximately 30% to 40% of the 1200 MPa measured for solid Ti-6Al-4V built in the EOS M280 machine [90]. While stress concentrations caused by the support structure geometry reduce the effective tensile strength of the samples tested, poor fusion in the support structure may also detrimentally affect the strength of the samples. To account for this the material of the XY cross-sectional area for \(\sigma_{\text{Measured}}\) are calculated using CT scans of untested tensile specimens for each sample type. For each sample tested, the tensile samples always failed in the first layers of support structure where they coincide with solid material.
CT scans of the first layer of support structure for each sample type are shown in Figure 5.7. The quality of fusion on the first layer of support structure is poor, with large gaps in what should be continuous material and solidified material forming agglomerates of varied thickness throughout the layer. The poorest quality of fusion for the first layer of support structure is found in Sample 1, where the support structure has the largest hatch spacing. The higher build quality in the first layer of support structure is correlated with
the decrease in the hatch spacing (Sample 1 → Sample 4), but gaps are still present even in the Sample 4.

Fig. 5.8: CT scan of tensile samples 1 mm above than the bottom support structure solid material interface: (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4

For support structure, the prescribed process parameters result in a reduction in linear heat input as compared with solid material. Default EOS parameters for solid material translate to a linear heat input of 0.272 J/mm for solid material whereas for support structure, the default linear heat input is 0.167 J/mm (62% of the solid material...
linear heat input). The poor quality of fusion shown in the CT scan images at the lower interface of solid material and support structure, see Figure 5.7, matches images presented in a parametric studies of laser power and scan speed for LPBF performed by Yadroitsev et al. [50,77] for single laser scans in LPBF. For the block type support structure geometry, each ligament of the support structure is processed as a single laser scan. CT scan images of support structure closely resemble single laser scans performed with insufficient linear heat input for proper fusion of material.

In addition to the decrease in linear heat input, the rapid conduction of heat away from the melt pool may prompt a further inability to sustain temperatures necessary to properly form the support structure. In the first layer support structure the solid material below acts as a heat sink due to its high mass compared to the support structure geometry, resulting in rapid cooling in the first layers of support structure. However, as the part height increases, the conduction to the substrate decreases and as a result overall heat loss is decreased due in part to the insulating effects of the metal powder [51]. This effect has been examined before by Yadroitsev et al. [50] wherein the quality of single laser passes, similar to single hatches used in the block type support structure geometry, were examined. In this study, the quality of the single passes improves with part height, as a result of the decreased rate of conduction with distance from the substrate. A conclusion from this study showed that single tracks built on large substrates require additional heat input to prevent losses from conduction. The difference in the prescribed material at the lower interface of support structure and 1 mm above that point is tabulated in Table 5.4. The
The parameter used to quantify the missing material is defined in Equation 5.3. The decreased conduction to the substrate with part height correlates with the improved quality of the support structure with height as shown by Figure 5.8 and presented in Table 5.4.

\[
\% A_{Unformed} = \frac{A_{Prescribed} - A_{Measured}}{A_{Prescribed}} \tag{5.3}
\]

The measured XY cross-sectional area of built material present at a specific height, \( A_{Measured} \) from Equation 5.3, in the part is measured using CT scan of untested samples.

Table 5.4: Percent reduction in the measured support structure material (Equation 5.3) at the solid material support structure interface (SMSSI) and 1 mm above the SMSSI.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>At the SMSSI</th>
<th>1 mm above the SMSSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 ((\Delta x = 0.70 \ \Delta y = 0.70))</td>
<td>7.0%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Sample 2 ((\Delta x = 0.70 \ \Delta y = 0.35))</td>
<td>10.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Sample 3 ((\Delta x = 0.35 \ \Delta y = 0.70))</td>
<td>5.0%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Sample 4 ((\Delta x = 0.35 \ \Delta y = 0.35))</td>
<td>5.1%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
When comparing the CT scan of the first layer of support structure material, with CT scan of the support structure 1 mm higher on the part it is clear the part quality improves as the support structure is built (Table 5.4). However, in a tensile test the support structure fails at its weakest point. Using image processing software, the amount of solid material was estimated for each CT scan image. Figure 5.9 confirms previous statements that the amount of solid material is at a minimum at the lower interface of solid material and support structure. As the support structure increases in height, its quality improves. Note that due to the poor quality of the build in the early layers of support structure, some of the solid material present in the CT scan at these heights may not be structurally significant. Figure 5.9 shows the percentage of solidified material for both the entire support structure, Figure 5.9(a), and a closeup of the early layers of support structure, Figure 5.9(b).
Fig. 5.9: Normalized percent solidified material versus part height from CT scans for Samples 1-4
Figure 5.9 provides an analysis of the quality of support structure with height. Samples take between 0.2 - 0.4 mm to recover from the poor quality in the early layers of support structure, this translates to between 3-7 layers of material. Although support structure improves in quality with height, during tensile tests and normal use, the weakest point of the support structure will cause failure.

Fig. 5.10: Image of the support structure fracture surface from sample type 1 after tensile testing\(^2\)

\(^2\)SEM images from Dr. Allison Beese, Shipin Qin and Lourdes Bobbio
Fig. 5.11: Magnification of the image shown in 5.10 highlighting the porous support structure material\textsuperscript{2}

Scanning electron microscopy (SEM) show the fractured surfaces both the support structure (Figures 5.10 and 5.11) and the solid material (Figures 5.12-5.13) after the tensile tests were complete. SEM images of the support structure, shown in Figures 5.10 and 5.11, highlight the surface roughness and porosity of the support structure in contrast with the quality of solid material, which is smooth and featureless. In addition, SEM images shown in Figures 5.10 and 5.11 provide additional evidence of the poor fusion in support structure showing sections where support structure was never fused to the solid material.
Fig. 5.12: Image of the support structure fracture surface from sample type 3 after tensile testing.

Fig. 5.13: Magnification of the image shown in 5.13 highlighting the poor fusion between the support structure and solid material.
5.5 Conclusion

The reduction of tensile strength in the samples tested is likely the result of stress concentrations resultant from the block type geometry used. Taking into account the poor fusion in the first layer of the support structure, the ultimate tensile strength of the support structure is considerably weaker (approximately 30-40%) as compared with the ultimate tensile strength of EOS built Ti-6Al-4V (1200 MPa) [90]. To further investigate the hypothesis that the poor build quality in the early layers of support structure is the result of insufficient heat in processing these layers, future work should include a process parameter study wherein laser power and scan speed for support structures is varied for similar tensile specimens. Tests should include the use of variable power with part height, where a high power is used in the first layers of support structure which decays to the default parameters with increase support structure height. Increased heat in the early layers of support structure may improve the overall tensile strength and reliability of LPBF built support structure. Additional testing should also include different support structure geometries.

Experimental results presented herein demonstrate the utility of measurement of mechanical properties for support structure. To effectively optimize the amount of support structure required for a specific build, it is necessary to be able to predict the strength of the support structure to prevent build failure. Measurements of mechanical properties of support structures from these experiments can be used in calculations and simulations
wherein support structure are designed to prevent residual stresses from resulting in large scale distortion and build failure. Further identification of mechanical properties of support structure will allow for future minimization of support structure while still maintaining utility, allowing for overall optimization of the LPBF build process.

5.6 Acknowledgements

SEM imaging and tensile tests were performed by Dr. Allison Beese, Shipin Qin and Lourdes Bobbio. This material is based upon work supported by NAVSEA under Contract No. N00024-12-D-6404. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of NAVSEA. The author would like to acknowledge Griffin Jones for performing CT scans of the tensile specimens.
Conclusions And Future Work

6.1 Conclusions

The goal of the work in this thesis is to provide experimental measurement and analysis of the laser powder bed fusion (LPBF) additive manufacturing (AM) process.

For thorough analysis of LPBF build process, it was necessary to develop an enclosed measurement system capable of providing in situ measurement of distortion and temperature during the build process that would not require modification of production scale LPBF machines.

- In situ measurements of temperature and distortion are used to compare and contrast experimental builds varying process parameters, materials, geometry and LPBF machines.

- A comparison between experimental builds made in two different LPBF machines, the EOS M280 and Renishaw AM250, is performed.

- Using in situ measurements of distortion, the stress relaxation resultant from the phase transformation mechanism present in Ti-6Al-4V is demonstrated for LPBF.
In situ measurements of the build process highlight inter-layer effects present in LPBF that cannot be captured by post-build analysis, identifying inaccuracies in the approach of some FE models for LPBF AM.

In situ experimental measurements of the build process are made using well-defined constraints on small test substrates with the purpose of implementation in the development and validation LPBF FE models.

Experimental measurements of post-build distortion profiles are presented for larger scale components.

- Experimental measurements show that for the thin-walled cylinders used there is no measurable effect of the constant versus rotating scan pattern in the distortion profile.

- Experimental measurements are used in the validation of a part-scale FE model. Validation shows the model to be within 12% error of the experimental measurements.

- A method is developed wherein a combination of FE analysis and post-build experimental measurements are used in conjunction to provide in situ analysis of the distortion and residual stress throughout the build process.

- For this part geometry, both experimental and simulation results show that distortion in the current layer is the result of the cumulative effect of subsequent layers solidifying and compressing the material beneath it.
Experimental results from tensile tests provide quantitative results of mechanical properties for LPBF built support structure.

- Tensile tests of LPBF built support structure are performed and show that the ultimate tensile strength of the support structure is 30-40% weaker compared with LPBF built solid material.

- CT scan images of the first layers of the support structure show discontinuities and agglomerates in the support structure, which are likely the cause of the reduced strength.

### 6.2 Future Work

Future work includes the implementation of the experimental results from Chapters 2 and 3 in the development and validation of future FE model for LPBF. A validated FE model can then be used in more extensive analysis, that is not feasible in experimental means. In addition, the combined post-build measurement and FE model analysis of LPBF built components described in Chapter 4 to more complex LPBF components can be extended to identify part geometries that result in large-scale distortion and build failure. Experimental analysis of the LPBF for full-scale components is limited by cost and time, but through the use of the validated part-scale model large process parameter maps can be completed to prescribe changes to geometries to improve final build quality.
Tensile samples similar to those from Chapter 5 should be built performing a process parameter study varying laser power and scan speed to determine the effect of increased linear heat input on tensile strength of support structure. Through this, a variable laser power with support structure height can be designated to ensure that the support structure interface with substrate is strong in comparison with interfaces that will be removed after the build process.

Future work suggested is necessary for full mechanical properties of LPBF built support structures. Inclusion of support structure mechanical properties into a FE model will allow the minimal support structure implementation while still providing confidence that build failure will not occur.
References


[38] Fessler, JR, Merz, R, Nickel, AH, and Prinz, FB, “Laser deposition of metals for shape deposition manufacturing,” *Proceedings of the Solid Freeform Fabrication Symposium; 1996 Aug 10-12; Austin, TX. University of Texas at Austin Publishers*, University of Texas at Austin, 1996


Validation,” Journal of Manufacturing Science and Engineering, volume 136, no. 6, p. 061018, 2014


[87] Sainte-Catherine, C, Jeandin, M, Kechemair, D, Ricaud, J-P, and Sabatier, L, “Study of dynamic absorptivity at 10.6 μm (CO2) and 1.06 μm (nd-yag) wavelengths as a


Vita

Alexander Dunbar received a B.S in Mechanical Engineering from Bucknell University in May 2011. Upon graduation, he enrolled in graduate studies at The Pennsylvania State University seeking a Ph.D in Mechanical Engineering. In May of 2015 he received his M.S. from The Pennsylvania State University for research on the development of CFD software for modeling the dynamics of offshore floating wind turbine platforms. After completing his M.S. in Mechanical Engineering, he transitioned into the field of additive manufacturing. His research interests in additive manufacturing include both experimental and modeling based analysis of laser powder bed fusion additive manufacturing.