

Trajectory Planning of Non-Gravity Aligned (NGA) segments in Arbitrary Directions for Large Scale Additive Manufacturing of Metals (LSAMM)

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To my wife, Hailey, because this wouldn't be finished without her. I love you.

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Abstract

Traditionally, slicing and path planning are done along the gravity-aligned direction of a part, causing more complex geometrical shapes to have unsupported overhangs. Wire Arc Additive Manufacturing (WAAM) has typically handled overhangs with a robotic part positioner; but, to extend the current capabilities of LSAMM, a new framework for slicing and building parts out of gravity alignment has been developed. The proposed framework focuses on segmenting more complex geometrical parts into gravity-aligned (GA), non-gravity aligned (NGA), and transition zones to support tool-path generation. GA and NGA segments can be planned with traditional slicing techniques, but the NGA tool-paths must be modified using open loop heuristics to ensure acceptable near net shape. The transition segment contains both NGA and GA features, making the planning more difficult as the geometrical complexity of the part increases. The goal of this framework is to interface different segments while maintaining consistent thermal conditions, all while ensuring build consistency and success.

A welding cell at the University of Tennessee-Knoxville was used to demonstrate builds for this work. Further builds were completed at the Manufacturing Demonstration Facility (MDF) at The Oak Ridge National Laboratory (ORNL). These builds were then scanned and used to characterize the effectiveness of torch heuristics for use in path planning techniques. The software used to generate path plans includes methods for planning, segmenting, and integration of a lumped capacitance thermal model which is used to predict whether overheating will occur within the build. The overall framework proves successful for building up to 105° of overhangs and has been used to manufacture complex geometrical features that were not previously achievable without using these methods. Future works needs to be done on improving the speed and execution of the thermal capacitance model, but it shows promise as a simplified method for predicting heat input into thin wall structures.

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Chapter 1

Research Motivation and Large Scale Additive Manufacturing of Metals (LSAMM)

1.1 Additive Manufacturing

After Chuck Hull produced the first concepts for 3D printing in 1983 [25], a paradigm shift was created in the way parts could be manufactured. This in turn has produced a significant amount of research in materials, controls, and design for Additive Manufacturing (AM). One thing has remained elusive throughout this search - the true 3D production of parts. Traditionally, 3D printing parts involves tessellating the surface geometry to produce layers for the AM process [52]. These layers are deposited layer by layer in order to produce complex 3D geometry. The traditional techniques have proved effective for some plastic and metal applications, but rely heavily on part pre-planning for build success given the limitations of process control on existing AM systems [18]. This type of 2.5D path planning has its own set of limitations for production of near net shape parts due to process limitations on the effectiveness of printing overhang features [41].

As AM systems improve, it begs the important question: Can we truly 3D print parts instead of relying on convenient 2.5D representation? If an AM system is robust enough

to print an arbitrary layer in 3D space, it opens up an entire new planning paradigm for these parts. Industrial robotic manipulators have been used in manufacturing for a variety of welding, part placing, and other various tasks [23]. However, current AM practices do not take full advantage of the capabilities of 6 Degrees Of Freedom (DOF) or greater robotic manipulators on achieving complex trajectories. Research on trajectory planning [2] and control [1] for robotic manipulators is a mature field due to new physical systems, control schemes, and machine learning techniques. Many current commercial AM systems rely on a part positioner to help simplify the path planning and resulting gravity effects from depositing material[14]. However, part positioners may not be a robust solution due to weight limitations for large geometries or if multiple arms are needed to work on a part [59]. Increasingly complex geometry, work space limitations, and multi-arm coordinated robotic systems must adopt new methods for achieving desired trajectories as robotic manipulators are leveraged for advanced manufacturing.

The current research methodologies need to be challenged in the manufacturing space to unlock the capabilities of AM systems to print true 3D parts. Specifically for Large Scale Additive Manufacturing of Metals (LSAMM), the process cannot use support structures to help build overhangs for complex geometry [40] due to labor requirements on removing the support material. Directed Energy Deposition (DED) processes, given their larger energy sources and material deposition rates, provide a perfect opportunity to explore the challenges associated with true 3D printing from the design of the CAD through path planning execution. Given that the standard industrial robotic manipulators can be used for DED processes, it also provides another opportunity to see how far current trajectory planning can be tied to AM processes.

1.2 Large Scale Additive Manufacturing of Metals (LSAMM)

The term metal Additive Manufacturing (AM) describes a variety of different processes used to build metal parts. Currently two types of additive manufacturing techniques persist in

metal AM industry: Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). PBF technologies were developed to give metal parts high resolution, but generally have a lower deposition rate. Highly specialized cabinets are needed to control the layer height, gas flow, and vacuum environment [27]. DED with powder feed technologies integrates powder with a laser heat source, which allows for variable heat input changes throughout the deposition. However, these processes have proven more complex to implement and the production of powder can be expensive [20]. Electron Beam FreeForm Fabrication (*EBF*³), laser wire-fed DED, and Wire and Arc Additive Manufacturing (WAAM) are all DED processes where wire is fed into the weld pool instead of powder. The *EBF*³ process, while having a large deposition rate, requires an airtight sealed environment to ensure the electron beam behaves correctly, limiting overall size based on the volume that can be sealed properly. Process stability without an inert gas environment has also proven to be an issue with Laser Wire Fed DED systems [10]. The WAAM technique typically relies on commercial welding equipment to deposit material with Gas Metal Arc Welding (GMAW) or Gas Tungsten Arc Welding (GTAW) power source [64].

LSAMM (specifically WAAM) has already been adopted for certain manufacturing areas such as aerospace [4], tool and die [24], and construction implement applications [42]. For a part to be designated "Large Scale," the part has the longest axis length at a minimum of 3-6 ft long [40]. LSAMM has gained traction in these industries due to expensive material costs associated with machining these structures using subtractive manufacturing [17]. AM techniques have become specialized to improve these issues by changing the material and power sources [41]. Large Scale Additive Manufacturing of Metals (LSAMM) has generally relied on higher cost processes due to lasers, powder, and specialized chambers; but, using a traditional manufacturing process like Metal Inert Gas (MIG) can help reduce the cost of deposition [63].

1.3 Wire Arc Additive Manufacturing (WAAM)

WAAM is a desirable process due to lower costs and it's relative simple nature when compared to other AM technologies. Most manufacturing centers already have the basic

robot manipulator and welding technology available and the cost for metal wire is relatively cheap when compared to the powders for laser processes [63]. WAAM processes have already been used in a variety of industrial LSAMM applications such as an excavator tool arm seen in 1.1.

WAAM research has focused on building parts to near net shape [12, 16]. As a standard manufacturing technique, there has been significant research on weld pool shape [19, 50, 15] material thermal behavior [13, 3], and the micro-structure of the resulting welds [30, 54]. However, the CAD-to-Path techniques developed specifically for WAAM rely on 2.5D path planning techniques, as seen in similar processes to Fused Deposition Modeling (FDM) of plastics [32].

The 2.5D approximation limits achievement of overhang segments in a given part due to holding the welding torch in a gravity-aligned (GA) orientation [33]. The stair-step effect produced by keeping the torch GA reduces the geometric accuracy and overall near-net shape of the as-built part [21]. Currently, if larger overhangs are needed in a part, a part positioner is used to rotate the build platform so that the welding torch orientation can remain constant [38]. Sometimes these parts weigh hundreds of pounds, so size and weight limitations must be considered when choosing a part positioner for specific applications. Another consequence of adding a part positioner is that the path planning becomes increasingly complex as commercial slicing engines and path planners introduce stair steps or eliminate overhangs all together [65, 8]. Achieving true 3D additive manufacturing becomes limited as current commercial capabilities do not take advantage of existing complex trajectory planning and control of industrial robotic manipulators[24]. Given these challenges, tying together all of the current capabilities with a new framework for trajectory planning of NGA segments and tying that into the overall CAD to Path plan is necessary to achieve true 3D printing. True 3D printing means that the capabilities of WAAM can be extended to larger overhangs and have as-built geometries reach closer near net shape.



Figure 1.1: As-built excavator arm from [56] showing a large scale AM part using a WAAM system.

1.4 Developing a Novel Framework for Achieving True 3D Printing

To achieve the goal of true 3D printing for LSAMM, a variety of different challenges must be addressed. These multi-disciplinary challenges sit at the cross section of material science, trajectory planning, and fundamental thermal behavior of welding. To realize these goals, a new framework for describing the path planning of a part must be realized. The framework must account for:

- Necessary torch orientation changes and positional changes from a pre-path planning standpoint
- Novel path planning tools and algorithms to help with part execution and organization
- Low level tools for control and planning of trajectory segments in terms of speed, velocity, and position
- Methodology for integrating the thermal effects of path planning to ensure part execution success

Experimentation and execution of segments for overhangs and increasingly complex geometry can be realized by providing a novel framework for LSAMM. The goal is to redefine path planning to provide low level execution based on feature type while also ensuring that the path planning segment organization can be modified by novel planning algorithms. The framework should be robust enough to print 2.5D and 3D segments while also integrating these two different segments into a single part plan. If this goal can be achieved, future experimental results can be used to supplement the path planning and trajectory planning for LSAMM. Successful integration of 3D segments into path planning will change the paradigm on planning and achieve overhang segments and increasingly complex geometry.

Work was completed at the University of Tennessee - Knoxville on the conceptualization and implementation of a novel framework for trajectory planning of these 3D segments. Chapter 2 will outline the fundamental motivations and definitions for this research and discuss previous work in LSAMM. Chapter 3 will outline the available technology and initial

steps taken to realize geometries for this work. Chapter 4 will outline the initial feasibility study using techniques of torch shift and rotation to improve the capability of achieving overhangs within this framework. Chapter 5 will detail the overall framework based from the feasibility study. Chapter 6 will detail use of the framework in performing a study on identifying an ideal NGA torch angle and shift for a representative geometry. Chapter 7 will then detail the methodology for integrating thermal effects to path planning. And finally, a summary of conclusions and implications for future work is detailed in Chapter 8.

Chapter 2

Literature Review and Fundamental Contributions

2.1 Traditional Path Planning for Additive Manufacturing

CAD to part methodology is one of the most desirable reasons to use AM. Part designers are able to use their Computer Aided Design (CAD) software of choice, upload the file to a Computer Aided Manufacturing (CAM) software to develop path plans, and finally export and run the path plan to build the part. A traditional design and build approach for additive manufacturing can be seen in Figure [2.1](#).

There are four steps for traditional additive manufacturing: design, slicing, machine code generation, and simulation. These four steps are interrelated, but have their own unique effects on the part plan. Some additive techniques use real time control to ensure build success [\[61\]](#), but they still rely heavily on the pre-part planning done in commercial software programs[\[32\]](#). The goal of the CAD to part process is to ensure that the part plan for the build maintains geometrical accuracy and strength of the final part.

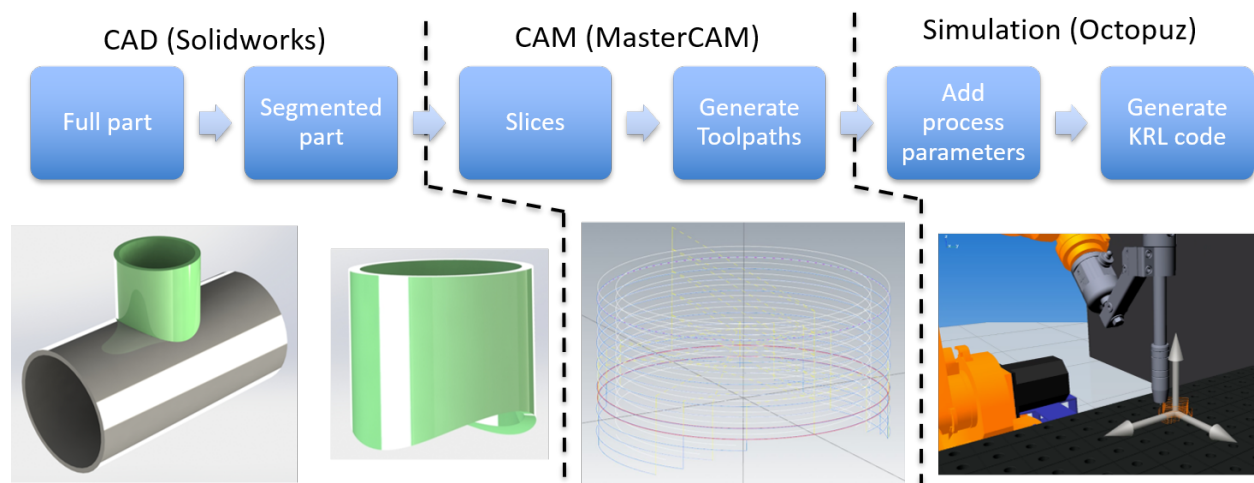


Figure 2.1: CAD to Part flow with details for LSAMM. This is the work flow from [33] outlining necessary steps for planning and executing path plans for AM parts.

2.1.1 Design

Additive technologies allow designers to implement complex shapes and geometries into their designs. However, the designers are still limited by the ability of the AM process to produce specific geometrical features [14]. Additive metal technologies still have issues with complex cavities and overhangs [49] because there is no way to easily implement support material. Powder beds use the non-melted powder as a support, but for DED processes there is not extra material for support [17].

The goal of the design stage of planning must ensure that any geometry can be built with a relative degree of accuracy [21]. Designers are limited by the process control for the system. Slicing and path planning can be modified, but part failures require design changes if slicing and process parameters cannot be modified. Since many additive manufacturing processes have been commercialized, the conditions that may lead to build failure vary by machine and process [10, 53, 17]. In the end, if a part cannot be built as designed for the particular AM process it must be modified to fit build process parameters or another manufacturing process be considered.

Current expectations of design features show overhang achievements for small segments of up to 90 degrees of overhang[6]. However these small features have been demonstrated but not executed for large part features. For the current state of the art WAAM process, the claim is 15 degrees of overhang [21]. However, recent research has pushed the limits by examining the humping phenomenon [67] and integrating Wire Feed Speed (WFS) and Travel Speed (TS) ratios for process changes into completing WAAM segments [68]. These have demonstrated up to 90 degrees of overhang for small segments - but rely on process changes within the power source to achieve.

2.1.2 Slicing

Slicing the part requires the part to have a digital representation. Once represented correctly, a slicing algorithm can operate on the geometry. The representation can be simplified down to two different types: solid and boundary [18]. Each type has its uses, and most

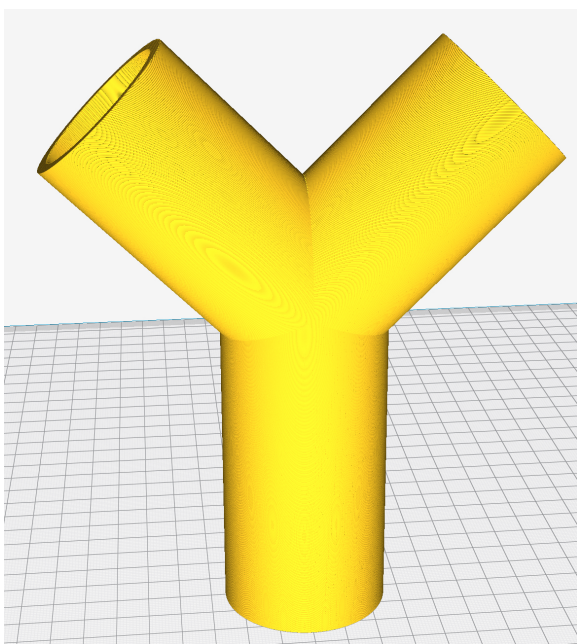
commercial slicers use boundary representation for the simplification of digital representation [65].

Standard Tessellation Language (STL) is the standard boundary representation [52]. Programs like Insight, MasterCam, and SolidCam all accept STL files as a surface file for building tool paths. The STL file type uses tessellated surfaces to represent the geometry of the part. This allows the part to be easily sliced for computer tool path algorithms. STL files are not the only boundary type, but are a standard within current AM processes [32].

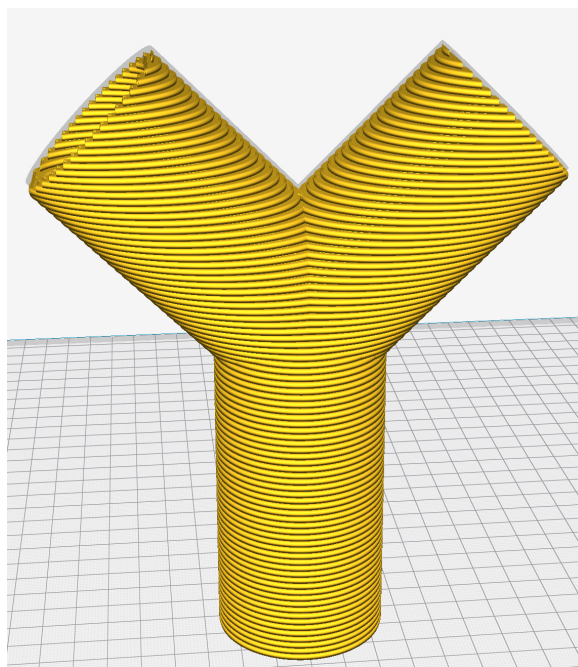
Voxels are typically used for volumetric representation [5]. Voxels reduce the part to a series of three dimensional squares. Voxels represent not only the boundary but also the inside volume of the geometry. The voxel representation makes it particularly effective for finite element analysis indicating bead geometry and interaction [9] or for thermal and residual stresses [13].

Either representation serves the end goal of mathematically defining how the slices will line up with the full part geometry. Without an effective digital representation, the part geometries cannot have successful path plans. The boundary surface requires less computational power to generate, but assumptions must be made within the slices of the geometry. Voxel representation is a more accurate representation of the volume, but higher resolution of voxels means more elements must be accounted for computationally [43].

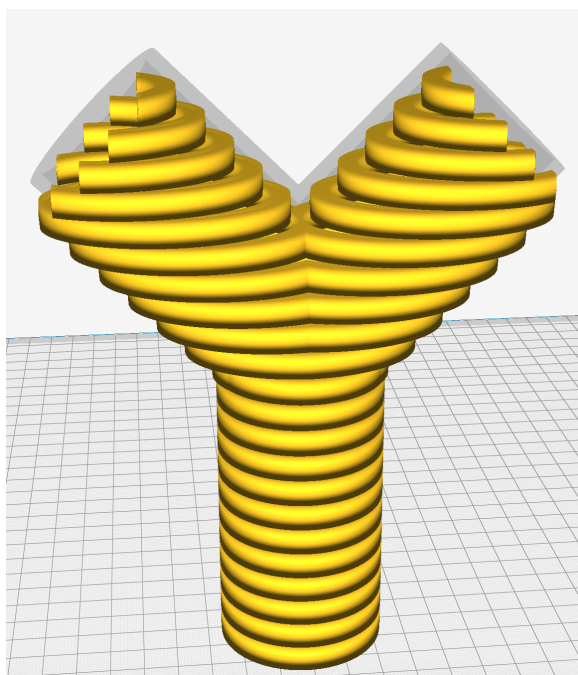
These slicing representations can greatly effect near net shape of the final part as illustrated in Figures 2.2a, 2.2b, and 2.2c. If a higher surface resolution is desired, more slices should be selected. However, as the thickness of the slice increases, the part plan begins to lose the accuracy and resolution of the original part, as seen in the shaded outline on Figure 2.2c. AM research has always tried to balance decreasing the time of the build while keeping the accuracy of final geometry [11]. While this example was shown using standard slicing, the problems persist for volumetric representation on representing near net shape of parts [66]. Tying the slicing to process parameters remains a constant challenge for AM, as different alloys, settings, and AM systems can have an effect on deposition geometry and height [28].



(a) 0.1mm Layer Height



(b) 2.0mm Layer Height



(c) 8.0mm Layer Height

Figure 2.2: Example of the effect of choosing layer height when compared to final CAD.

2.1.3 Machine Code Generation

Machine code generation requires assigning tool-paths for the system with the correct deposition settings. Typically these settings are tied to the available hardware which would produce a certain weld bead size to fill a space [14, 60]. Many existing Computer Aided Manufacturing (CAM) programs exist that combine slicing and code generation into one. Insight for FDM printing from Stratsys is an example of a CAM software used for 3D printing. The slicing is specified by the user and the machine code is generated directly from the slicing of the part geometry.

CNC and 3D printers typically use G-code as the standard for building tool paths. G-code is a globally standard representation of the tool tip movements within a Cartesian Coordinate System (CCS) [51]. G-code has the ability to be imported into most CAM software and converted to the appropriate machine tool control code. G-code does not typically specify the welding settings, which can be set offline or through a unique robotic controller. Welding process changes are power source specific, meaning coordination between the power source and robot controller adds another layer of integration with any DED system [20]. Therefore, integration of the correct machine code settings is critical.

Additive manufacturing has tried to take advantage of the process parameter changes using adaptive slicing [26], optimized path plans [9], and heuristic rules [6]. Given infinitely complex geometry, human intervention is required on the design or addressing the limitations of the specific AM processes to ensure successful near net shape is reached. Expanding the slicing and machine code generation will require knowing the capabilities of power sources to change settings during the build, as well as providing a framework for use across multiple types of power sources and robotic code.

2.1.4 Simulation

While simulation of paths has been well shown in literature for robotics and CNC milling [29, 3], the thermal evolution of the part often is the most important factor for ensuring build success during LSAMM. Research in understanding the effects the thermal gradient has on grain structure and build success has been extensively studied for other AM processes

[7, 53, 22]. LSAMM build success in particular is dictated by the thermal effects that a large moving heat source can have on the build [54]. High distortion, lack of fusion between layers, and poor final material properties can be the result of mismanagement of the thermal evolution of the part [30].

Researchers have used Finite Element Analysis (FEA) to help predict the thermal history of a DED part, as seen in [56]. Increasing the number of voxels also increases the number of numerical equations that must be solved, and typical FEA can take hours or days to complete. Other researchers have focused on simplifying assumptions to the FEA to improve run time [13]. The path planning step for WAAM processes should include the necessary methodology to integrate a simplified thermal model to identify hot spots, possible meltdowns, and ensure proper material properties [69]. If the path plan can stay within an acceptable range of not too hot and not too cold (the "Goldilocks" Zone), acceptable material properties and weld pool stability can be achieved.

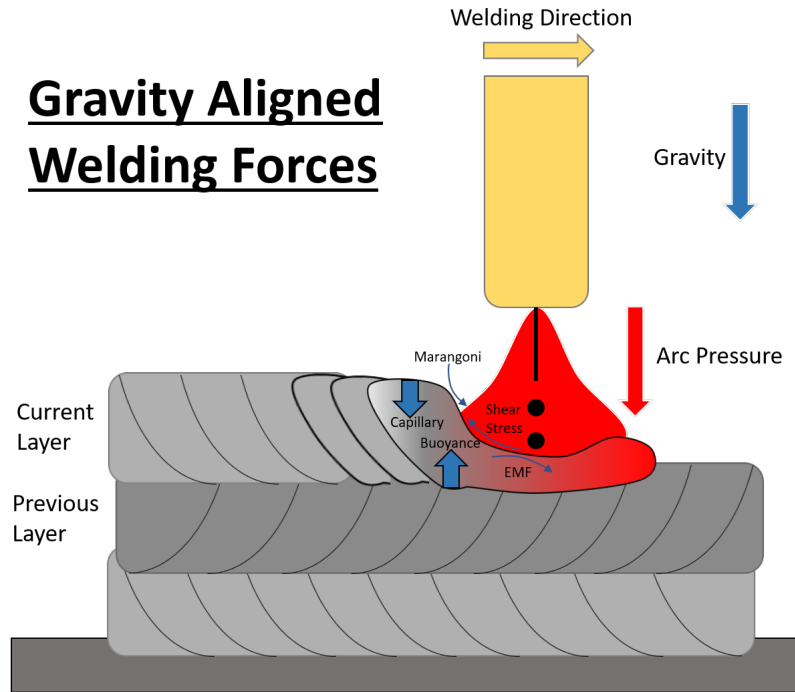
2.2 Gaps in Current Research

2.2.1 Non-Gravity Aligned Segment Pre-Planning Strategies

Previous WAAM research has used external axes or gantry systems to keep the part Gravity Aligned (GA) [12, 16, 29, 44, 40]. A major research gap is building Non-Gravity Aligned (NGA) features without the use of part positioners. The behavior of the weld pool in NGA and GA segments are completely different, even for similar welding settings. The changes make identifying the differences between design, slicing, machine code, and simulation for each type of these segments a dynamic challenge. Given the amount of trajectory planning for industrial robotics, there is a major lack of trajectory planning specifically for AM that integrates complex 3D trajectories. Identifying proper torch angles and shifts will utilize the arc force of the welding process to maintain the weld pool shape and thus produce the desired weld bead geometry. This is done by re-orienting the welding torch so that the force vector of the arc force begins to counteract the gravitational force (see Figure 2.3). The figure illustrates that when operating in a GA orientation on a flat wall the forces associated with welding are easily counteracted, and the capillary force of the weld pool will keep a desired weld pool shape. In the NGA Welding case, not using the arc pressure to counteract the effects of the gravity forces on the weld pool could result in undesirable bead geometry due to capillary forces being overwhelmed by the force of gravity, resulting in the weld drooping or completely dripping off of the segment. This type of NGA welding (also known as "out-of-position" or "positional" welding) has been used in conventional hand welding as well as automated groove filling to perform welds in difficult to reach areas [19, 50]. Due to the volatility of maintaining weld pool stability, skilled welders need many hours of practice to get the certifications for out of position welding. Given the advances in industrial robotic path planning and control techniques, bridging this information and experience gap between welders and roboticists lends itself perfectly as a research space for increasing the complexity of trajectories that can be achieved and executed for AM processes.

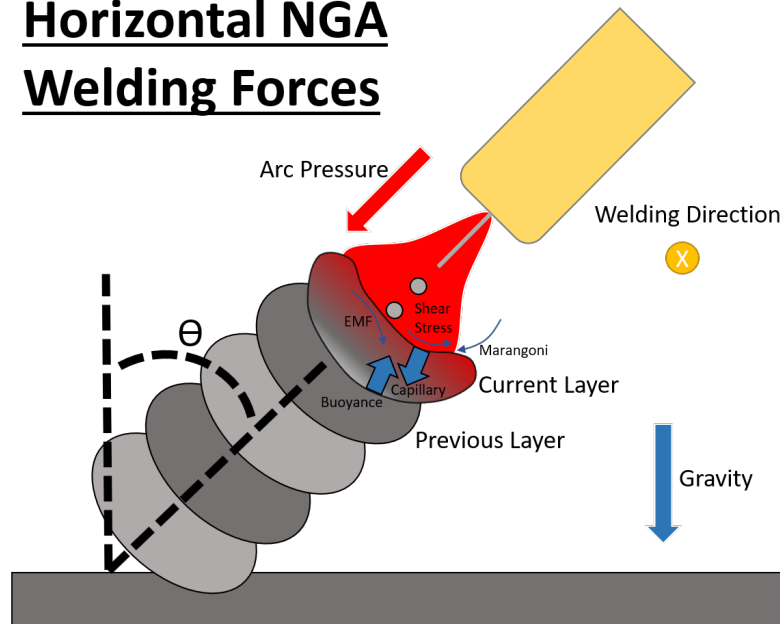
In the case of additive manufacturing, some work has been done in investigating the effect of the torch angle on the formation of the weld pool. [67] diagnosed the cause of humping that occurs in NGA WAAM based on the wire feed speed (WFS), travel speed (TS), and

Gravity Aligned Welding Forces



(a) Gravity Aligned (GA) Deposition on a standard AM section of wall

Horizontal NGA Welding Forces



(b) Non-Gravity Aligned (NGA) Perpendicular Deposition on a horizontal overhang section

Figure 2.3: Static force balance on an out of position weld pool with different welding positions. θ is the overhang angle for the Horizontal NGA welding of overhangs. The force balance will change based on the torch position with respect to the gravity vector.

deposition direction. Then in [68], the researchers applied their findings to investigating the construction of vertical and horizontal walls and determining an operating zone for specific welding parameters. WFS and TS are vital for successful WAAM part completion, but it would be desirable to introduce non-process related changes to the part plan to achieve desired near net shape. Process changes can effect resultant bead geometry [37] but also resultant material properties [54]. From a robotic planning and control perspective, generalizing bead geometry and then using the robot to achieve the desired bead shape without modulating the process settings would help ensure a more stable operating window. This is particularly true for cases as seen in Figure 2.4 where the desired angle of the weld torch is limited due to interfering overhang segments enclosing on each other.

Isolated NGA segments are easier to achieve because collisions are easily avoided. For more complex geometries there may be NGA segments that are competing for the operating space of the robot during path planning, resulting in the torch collisions given improper trajectory planning. Researchers have tried to improve overhang feature completion using process settings [6], but a unique approach would be to determine how much position shift and angle change for the overhang is necessary to produce desired bead geometry. Cartesian changes to the path can be mathematically implemented given a desired overhang angle and expected bead geometry. The Cartesian path changes also moves away from modulating torch parameters during the layer, allowing the thermal properties to be similar across the whole segment. A simplified diagram of this angle and position shift is illustrated in Figure 2.5.

Initially, these path planning techniques must rely on heuristics due to the capabilities of the chosen deposition process and path planning limitations. However, simplifying path planning to a simple position and rotation shift can allow algorithmic planning of NGA segments given proper heuristics of the deposition process and overhang feature types. These results could then be extrapolated to other systems based on experimental results.

2.2.2 Transition Zone Planning

Enabling the CAD to Part planning to include multi-directional planning techniques would enable LSAMM systems to be used to their full trajectory planning potential. Some

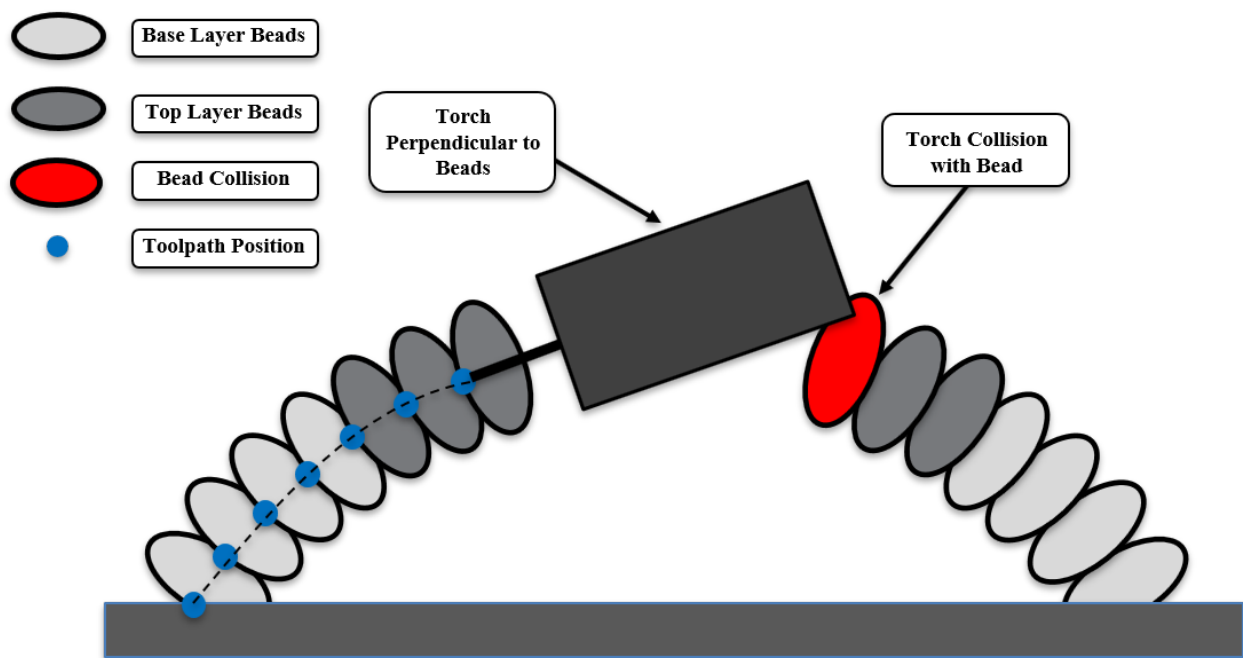


Figure 2.4: A generalized example of an enclosing NGA part where a torch orientation would interfere with the opposite side geometry.

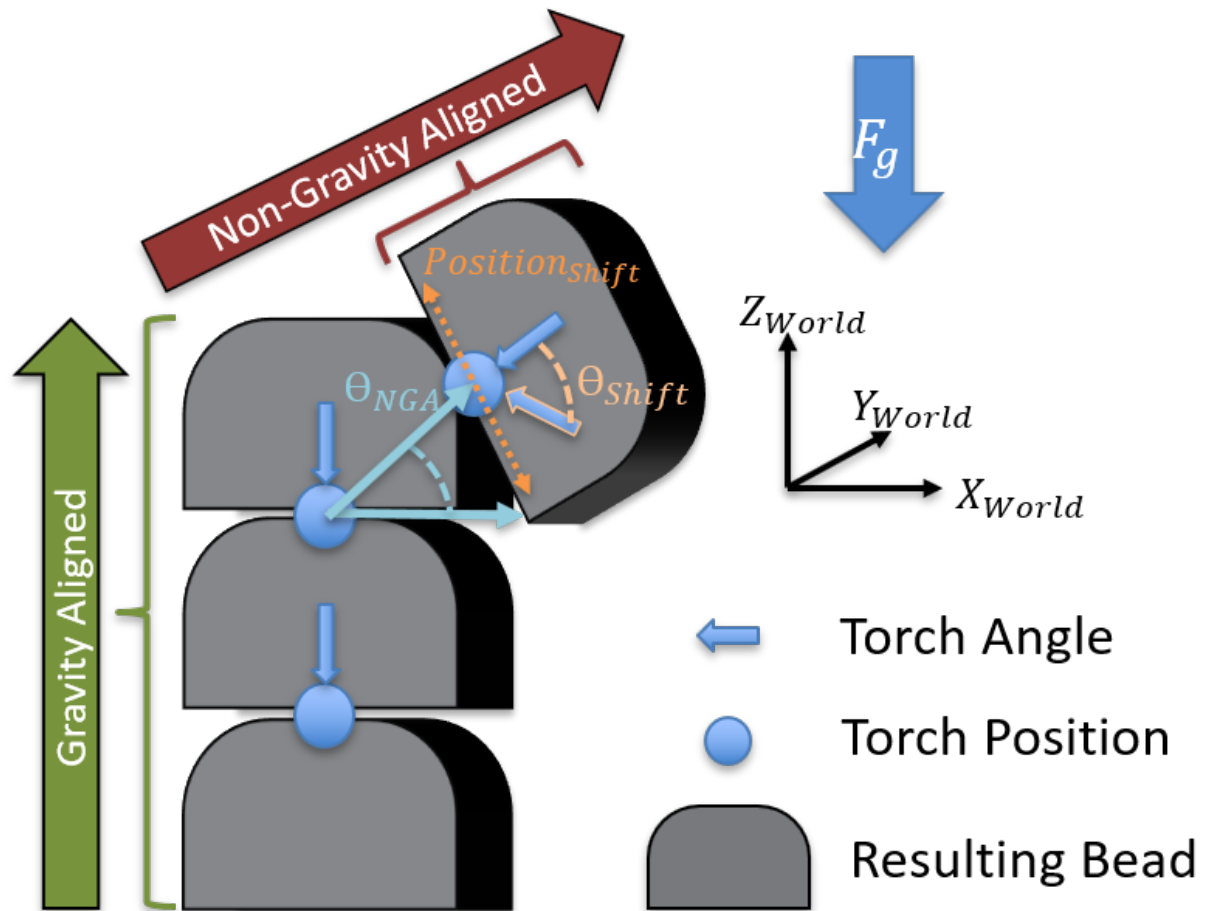


Figure 2.5: A simplified diagram showing the definition of torch angle and position shift.

researchers have built algorithms which can handle multi-directional slicing of simple parts [57, 11, 39]. However, these slicing algorithms still suffer from inherent issues regarding planning the transition zones for more complex geometrical shapes. The transition zone is a section between a GA and NGA section that contains both properties of GA and NGA sections [57]. Figure 2.6 shows the transition zone as the yellow section of this geometrical shape. It is unclear how to slice, plan, and execute such sections due to overhang and process limitations, so designing a software framework that allows a user to utilize new slicing and path planning techniques is a necessity. Traditional geometric slicing (2.5D slicing) may not be ideal for transition segments given the current process capability with AM systems. New techniques for planning these transition zones and reducing the stair-step effect seen for traditional AM technologies can be identified when a framework that can generate, modify, and execute these 3D segments is implemented on a DED system. This software and resulting planning framework can then be modified to execute algorithms on specific path planning segments as each of the varying segment types can require different execution.

2.2.3 Thermal Considerations for LSAMM

One of the greatest challenges for LSAMM is controlling the heat input into the build to assure proper material properties and near net shape. Poor thermal management typically results in build failures like part meltdown or high enough residual stresses that the part distorts such that the build cannot be completed. The thermal gradients present within a build have been observed for microstructure and residual stress analysis [48, 13]. For a process like WAAM with a powerful input heat source it is easy to cause build failures due to poor part planning. Given identical welding settings but an improper direction and sequencing of the layers can be the difference between successfully building a part versus part meltdown. Welding settings are important for builds, but the sequence in which the welding settings are applied is just as important.

Attempts have been made in [13, 56, 9, 48] to model specific AM processes to a high degree of fidelity. Most of these attempts were not used to make planning decisions, but to gain insight into the failure modes and stresses within the part. Modeling must be used for influencing the process planning decisions that will be necessary for LSAMM, particularly for

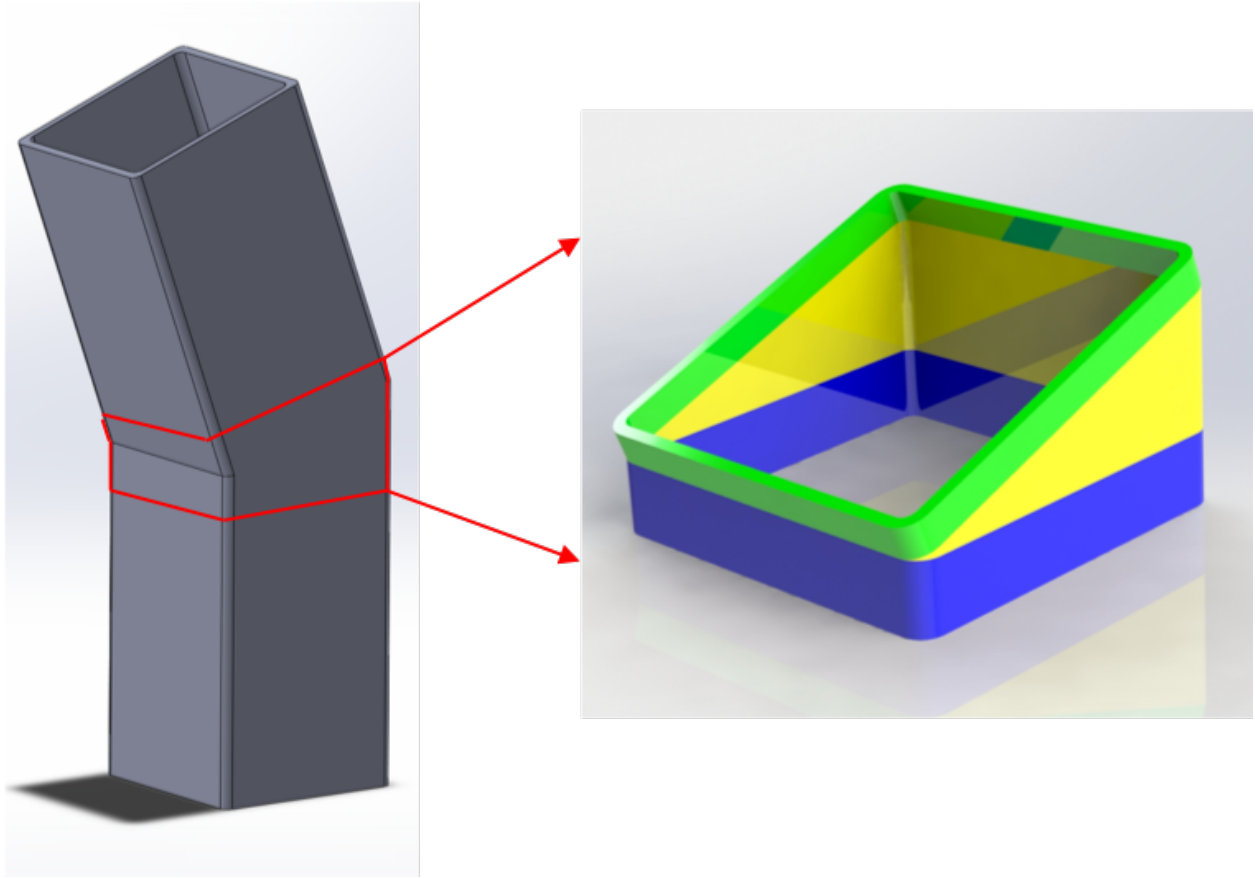


Figure 2.6: Breakdown of the simple geometry into the different types of segments. Blue represents a section that can be build Gravity Aligned (GA), Green Represents a Non-Gravity Aligned(NGA) section, and the yellow section is a Transition Zone.

NGA segments. If a section becomes too hot, the part may melt down and droop, causing deviation from desired near net shape. An ideal temperature "Goldilocks" zone needs to be identified to ensure material properties and reduce failures during and after the build. Thermal management becomes even more challenging when the torch is not aligned with gravity due to the gravitational effects on a molten melt pool [15, 19].

2.3 Motivation

The fundamental goal of this research is to provide a CAD to Path trajectory planning framework that can account for many aspects of path planning with regards to complex path planning segments like overhangs. The framework should be robust enough to plan geometry that grow in arbitrary directions, all while giving the end user tools to ensure the build success. After the framework has been developed and implemented, fundamental torch heuristics pertaining to overhang segments can be identified and developed. Development of this framework will allow algorithmic implementation of NGA methods during the path planning stage, allowing a deeper understanding on the effectiveness of open loop path planning. Finally, given the framework and the fundamental understanding of the heuristics with regards to path planning, a simplified lumped thermal model will be integrated into the framework. This will allow the user to ensure in pre-build that the plan will be successfully completed and have a high degree of confidence on the resulting material properties. All of these fundamental contributions are directed at extending LSAMM path planning to include and integrate complex 3D segments that can be achieved by industrial robots.

Take for example the geometry in Figure 2.6 of a square tube that can be used for vehicles or large structures. If someone desired to use AM to build this part, the path planning could be simplified by identifying that three unique types of sections exist within this part: GA (blue), NGA (green), and a transition zone (yellow). The blue section could be completed by keeping the deposition head Gravity Aligned (GA) for the entire blue section. Once the part reached the yellow section, the transition zone, these new segments could be planned using a variety of techniques, like the ones seen in Figure 2.7. So what way is the best way to plan this part? The answer depends on system settings, material properties, and the capability

to complete overhangs. The final fundamental contributions for this work are summarized below:

- Creation of an effective CAD to Part trajectory planning framework for GA and NGA Build Directions
- Heuristics pertaining to the integration of GA, NGA, and transition zone tool path generation using torch position and orientation
- Development of Simplified Thermal Prediction for NGA CAD to Path Evaluation for LSAMM parts

While the end goal of this research is an integrated and effective CAD to Path framework, it is recognized that this type of path planning may not be effective for all types of DED processes. Generalizing these concepts discovered from the WAAM system needs to be done so that these can be applied to new AM systems. If these concepts can be improved upon by future robotic control and further software integration, this research will serve as a great first step into full development of a CAD to Part process. These processes can build parts in arbitrary directions with increasingly complex geometrical features, thus opening the door to true 3D printing capabilities.

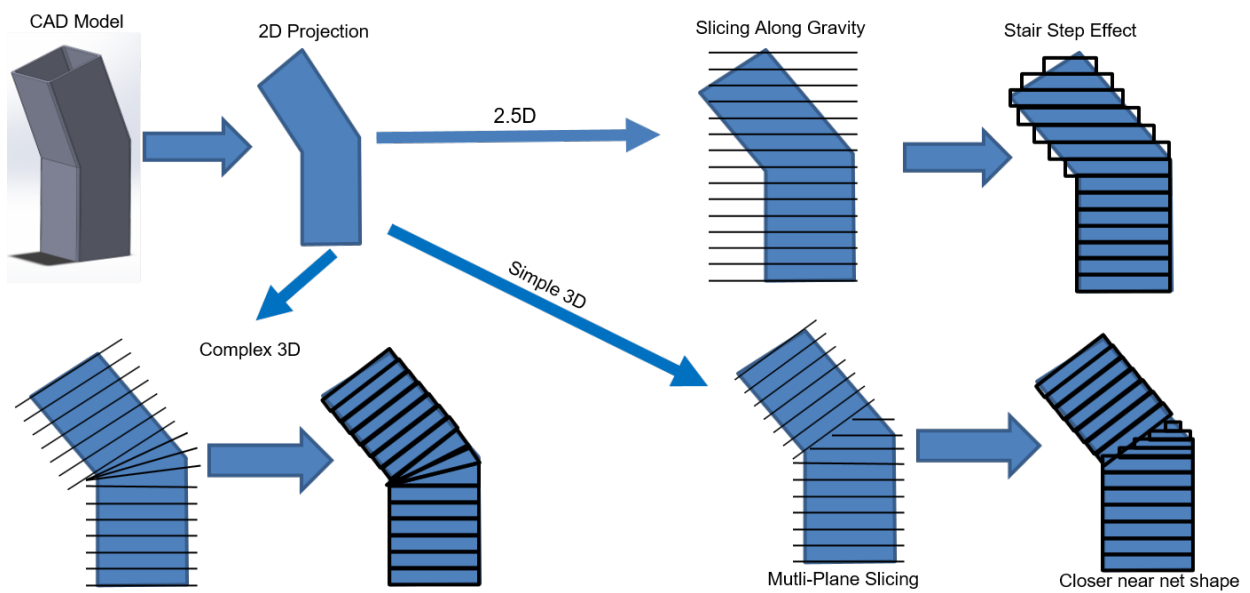


Figure 2.7: Adapted from [58], this shows multiple choices available in planning transition zones with variable-height and multi-direction slicing techniques.

Chapter 3

Physical System and Research Goals

3.1 Experimentation System and Settings

Consistent process settings are necessary to help ensure that the heuristic effects seen by testing NGA methods are effective. Therefore, a generalized low carbon steel wire and short circuit process were chosen for all geometries seen in Chapters 3-7. The Regulated Metal Deposition (RMD) process was used on the welding cell located at the University of Tennessee. RMD is a short circuit process and was chosen due to its low heat input compared to other WAAM processes [55]. In addition, no closed loop system control was used for these builds. All path plans were followed with no closed loop control action taken to ensure layer consistency or to maintain constant nozzle to work-piece distance. Composition of the standard welding wire used for all experimentation can be seen in Table 3.1.

Relevant build parameters can be seen in Table 3.2. The only significant differences between builds is switching from 92/8 Argon/Carbon Dioxide to 95/5 Argon/Carbon Dioxide content for later builds. The lower carbon dioxide content helps reduce the heat content of welding due to the lower activation energy of Argon, and it was decided to use the 95/5 after some experimenting with various percentages of CO₂. The welding cell at the University of Tennessee can be seen in Figure 3.1. Initial welding parameters and bead sizes were determined from previous work in [47] through single bead and simple wall experiments. The process parameters are on the lower end of welding parameters in terms of heat input for this type of material and RMD process, and are outlined in Table 3.2.

Table 3.1: Wire composition of ER70S-3 [36]

C	Mn	P	S	Si	Cu	Cr	V	Ni	Mo	Fe
0.06	1.06	0.006	0.012	0.47	0.18	0.06	<0.01	0.04	0.01	Rest

Table 3.2: Standard welding parameters used for printing in any direction

Parameter	Value
Process	RMD
WFS [in/min]	130
Travel Speed [in/min]	6.5
Arc Control	25
Arc Adjust	50
Voltage [Volts]	15
Current [Amps]	80
Initial Wire Stickout [in]	0.5
Gas Composition	92%Ar, 8%CO2 / 95%Ar, 5%CO2

The values in Table 3.2 produced an expected bead height of 2.25mm and expected width of 6mm. These values of bead thickness and height will be used to develop the desired CAD and path plans. These bead heights and width were shown from measured caliper thicknesses and heights from WFS to TS ratio parameter testing. The welding process settings were kept constant for all experiments to ensure that the effect of torch rotation, position shift, and sequencing changes could be delineated from other process changes. With a decent initial set point on welding settings these techniques should be able to transfer for new systems or different settings. For this work, only thin wall geometry is considered, as filling has been well shown to be a complex problem with bead interaction and mixing [9, 31, 14].

3.2 Generalized Geometry Example

To establish an initial baseline for building parts with the system from Figure 3.1, an initial complex geometry (Figure 2.6) with GA, NGA, and a transition zone segment was chosen. The path plan was generated using the CAD to Part methodology from Figure 2.1. The major steps of segmentation and slicing were done using a combination of Solidworks and MasterCam to plan the segments, while Octopuz was used to simulate and export the machine tool path. Layers were programmed and sliced by hand due to lack of customized software packages and commercial slicing techniques.

The planning for the transition zone was kept simple by assuming that it could be stair stepped along the interface with the NGA section. This assumption allowed both the GA and transition segments to be built using traditional 2.5D GA techniques. The NGA section was initially assigned a tool path with the welding torch perpendicular for the path. An illustration of the tool paths are seen in Figure 3.2. The green arrows represent the start and direction that the contour will be deposited while the red arrows represent the end of the path. The designed overhang angle for the NGA segment was 35°, which is slightly above the known capabilities for overhang segments deposited with simple GA methods [21]. The overall box dimensions were 5 inch sides, with an NGA and GA segments being made up of 20 layers. The transition zone contained 62 layers with varying lengths based on building the stairstep segment.

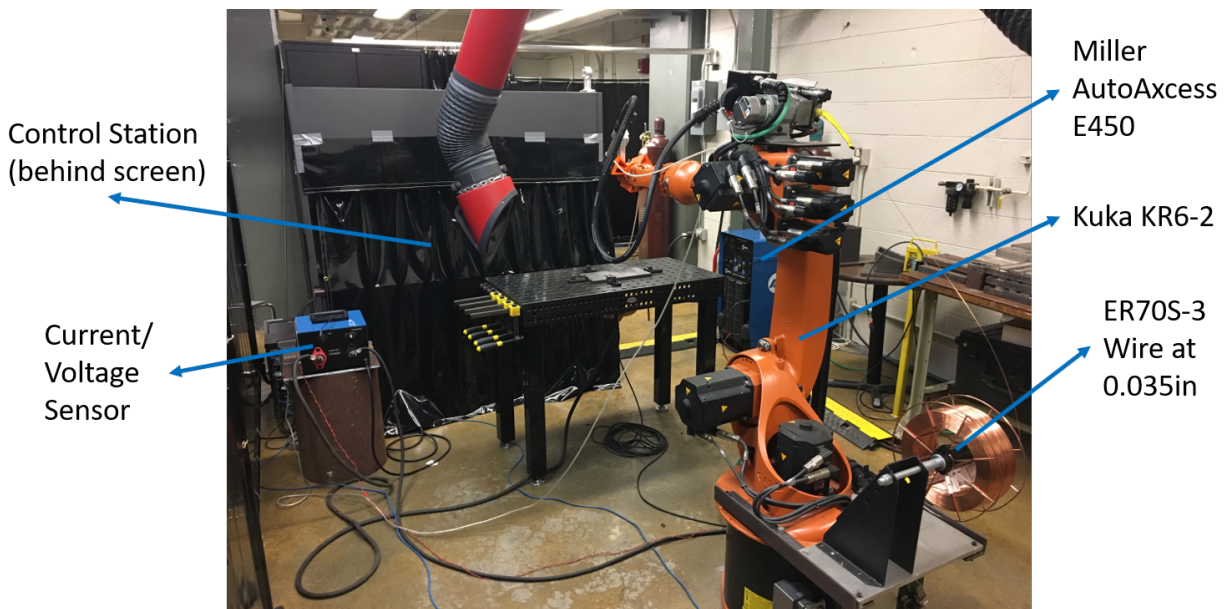


Figure 3.1: Wire and Arc Additive Manufacturing work cell at the University of Tennessee

Segment Planning for GA, Transition, and NGA Sections – Initial Planning

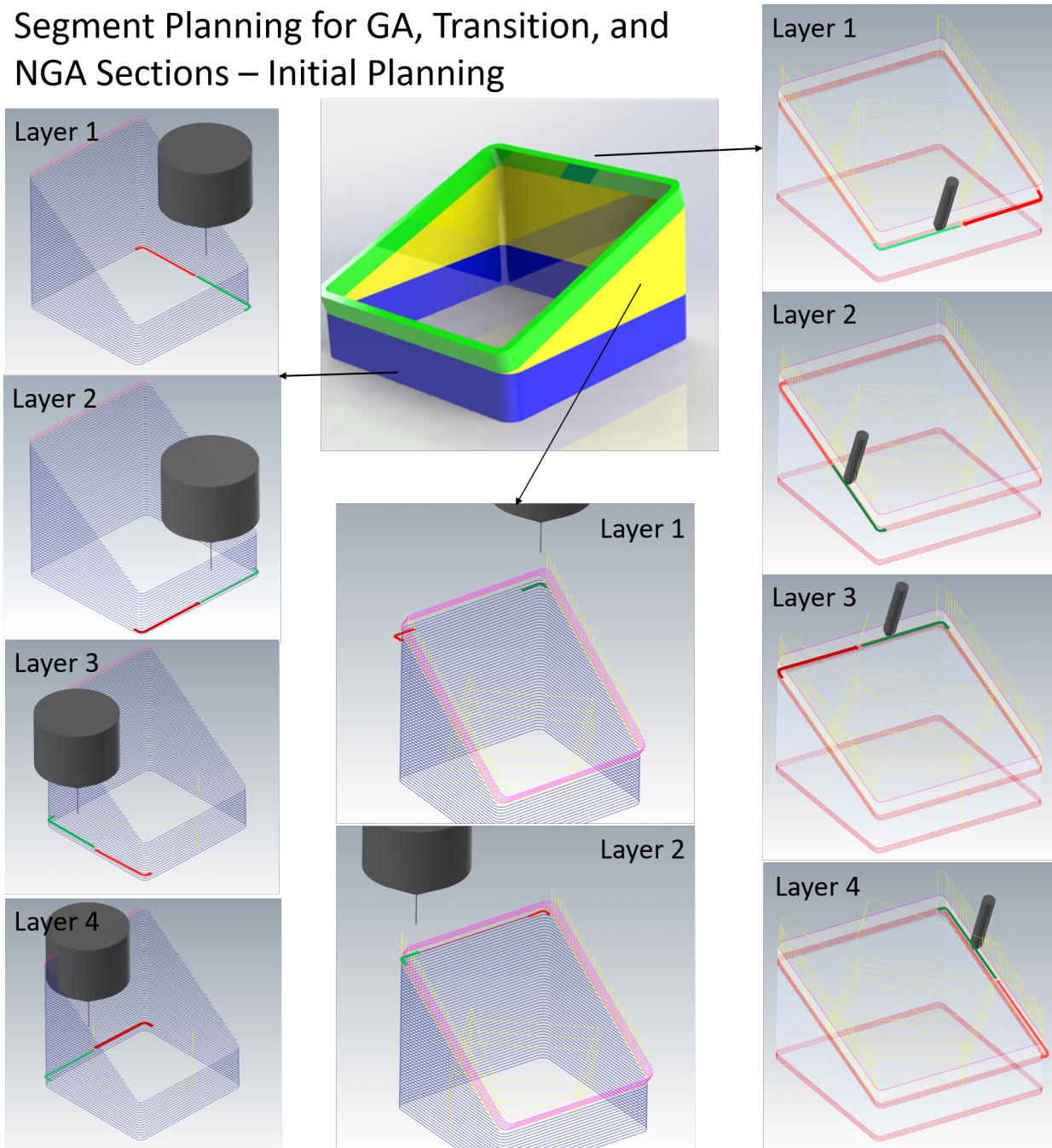


Figure 3.2: Planning for the initial complex part plan. The plans are separated by the GA, Transition, and NGA sections. The NGA section had a perpendicular torch angle for the NGA Section.

The final result of the build can be seen in Figure 3.3. While only 5 layers on the NGA section completed, it is already observed that on the uphill/downhill welding that the start stops are proving to be problematic for near net shape. Secondly, there is a significant difference in bead deposition height when welding downhill vs. welding uphill. Uphill welding is defined as moving the torch against the flow of the weld pool, while downhill welding is the opposite direction moving the torch with the flow of the weld pool. Even though the layer paths alternated directions, the consistency of the paths was poor. Finally, when trying to complete the NGA segment, the welding wire missed the part due to the NGA segment drooping much lower than the expected path - resulting in the part not being completed. The initial results pointed that implicit understanding of the physical effects happening within each contour needed to be identified so that appropriate actions could be taken for the next iteration of the complex part geometry.

Three main areas were identified for improvement on the next iteration of the complex part: torch angle relative to overhang angle, alternating directions versus downhill welding only, and placement of the start stop points on the layer. All of these improvements stem from improving the NGA section, as it was the only section which was not completed in the initial build. New base plates mounted at 45° provided a clean surface and higher angle than the expected complex geometry. The goal of the experiments was to clearly see the physical effects of the resultant bead geometry. A summary of these experiments and their results can be seen in Figure 3.4 for reference.

The first question was determining what torch angle of the deposition head relative to the overhang angle would be best for certain overhang segments. From the Figure 3.4 Perpendicular vs. Angled, it can be seen that even a slight 10° difference causes significant changes in the deposited weld bead. The 90° (or perpendicular torch) can be seen to have a higher frequency of deviations from the surface across the top and bottom NGA segments, while the more angled was smoother but had larger deviations. The more angled allowed the top surface from the downhill welding to look much better from a top and side layer perspective.

The effect of only traveling downhill is more clearly illustrated in Figure 3.4 Alternate Direction vs. Downhill Only. The blue arrows represent the travel direction of the deposition

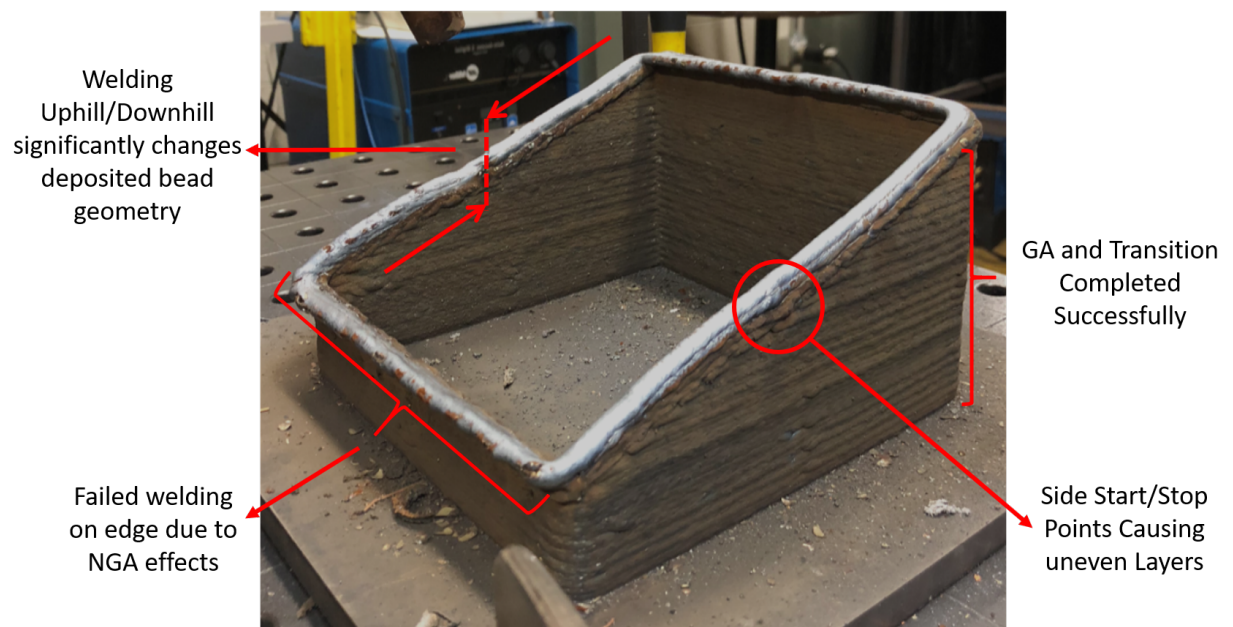


Figure 3.3: The initial complex part as built. The GA and simple transition zone completed successfully while the welding failed on the NGA sections due to long arcing from the weld bead drooping too low on the upper and lower NGA section.

head and it can be seen that only welding downhill produces significantly smoother beads and side surface geometry. However, the accumulation effects in the corners seem to be worse when only welding downhill versus alternating uphill and downhill since the bead is always only flowing downhill.

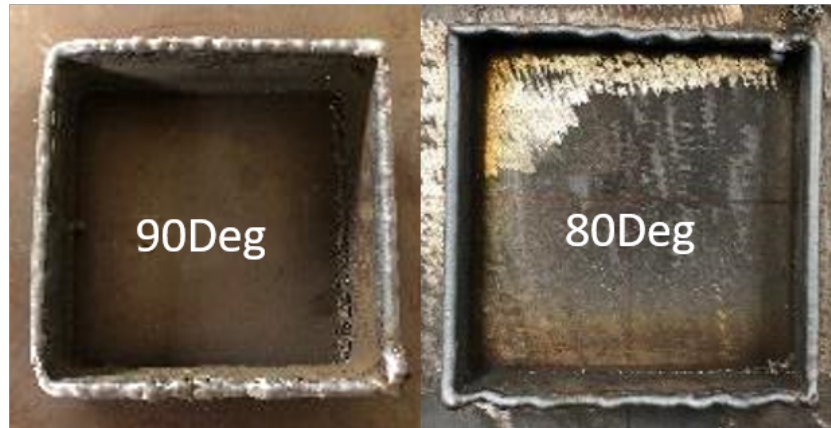
And finally, the start and stops were moved around on the upper and side segments of the box geometry. Due to the transient effects of start stops having a different deposition and accumulation rate than steady state travel in the NGA, it was determined that more start stops along the top and bottom sections would be ideal given their inconsistent accumulation effect. The differences between having 2 start stops on the same segment versus 5 start stops can be seen in fig. 3.4.

The implications of these simple experiments show that torch angle, sequence, and shift along the path can produce these NGA segments without having to vary the welding process while depositing. The simple techniques were used at a greater angle than the complex geometry, and significantly improved final near net shape for the NGA segment. However, given that the effects vary because of the orientation of the torch and resulting deposition, new naming conventions are needed to help identify which techniques should be used. A summary of these naming conventions and effects are defined as follows:

- NGA segments should be split into 2 different types: Horizontal and Vertical
- Vertical NGA segments indicates that the torch is welding uphill or downhill during the build, causing the weld bead to flow along the tool path center line
- Horizontal NGA segments are defined as when the torch is welding side to side, causing the weld bead to flow away from the tool path center line
- Horizontal and Vertical NGA segments have different behaviors when welding NGA due to gravity effects on the weld pool and must be accounted for in path planning with different sequencing and torch compensation techniques

For a cross sectional geometry like the complex part from Figure 2.6, there are 4 sides of the part which contain two vertical and two horizontal NGA sections. Given that the vertical NGA sections will have the bead flow downhill relative to the base angle, it was determined

Torch Angle: Perpendicular vs. Angled



Alternate Direction vs. Downhill Only



Start/Stop Point Variation

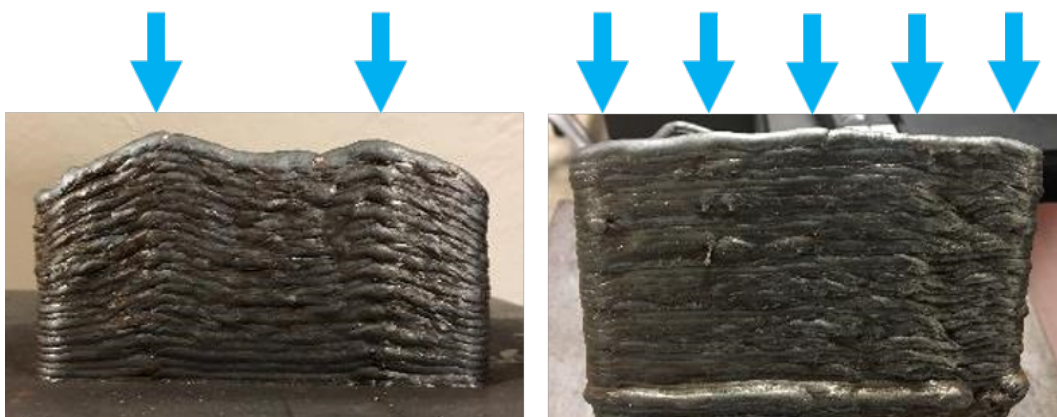


Figure 3.4: The effects that varying, non process changes can have on the as built geometry of NGA segments. These are just some of the more successful examples of initial experiments and the differences they can make on the part plan.

that the vertical sections should always move downhill, producing a much smoother and consistent layer. The Horizontal NGA looked better with a torch angle perpendicular to the previous segment, while the vertical segments preferred a steeper angle relative to the base plate to help push the bead slightly uphill. The NGA segment was modified to only have layer starts on the top horizontal NGA segment, and only have layer stops on the bottom horizontal NGA segment. To reduce accumulation effects due to starts and stops, there were 5 varying stop start points on the upper and lower Horizontal NGA segments. The GA and transition sections used the same torch angle and sequencing and the part was re-deposited. The results of the final CAD to Path plan can be seen in Figure 3.5. The part plan was executed on the welding cell and the final results can be seen in Figure 3.6¹.

The updated complex part plan completed successfully, finishing all 30 layers of the NGA section. However, observing Figure 3.6, there are major deviations in the consistency of the heights for the corners of the NGA segment. Even though corrections were made from the initial complex part build, the interaction between the vertical and horizontal NGA types in the corners caused significant deviation from the expected bead geometry. The bottom corners were near the expected height, but the top corners were under-built 6mm from the expected build height, almost 3 layers shorter than expected. The interaction between gravity, weld pool, and previous layers creates a complex weld pool interaction that is hard to predict and compensate for with simple sequencing and small torch angle changes. The bottom corners are building at the correct rates, but removing uphill welding on the vertical NGA segments caused the vertical NGA sides to under build from the expected layer height. This was especially evident when comparing the top and bottom corners as the bottom corners are much taller due to weld pool flow.

3.3 Identified Areas of Research for Improving Overhang Quality and Path Planning

The main takeaways from the initial attempt of the complex part are clear, given the success from the first to second iteration. The first takeaway is that although the final

¹A full video of the Complex Part build can be seen here: <https://youtu.be/wXn0x9ZG8Sc>

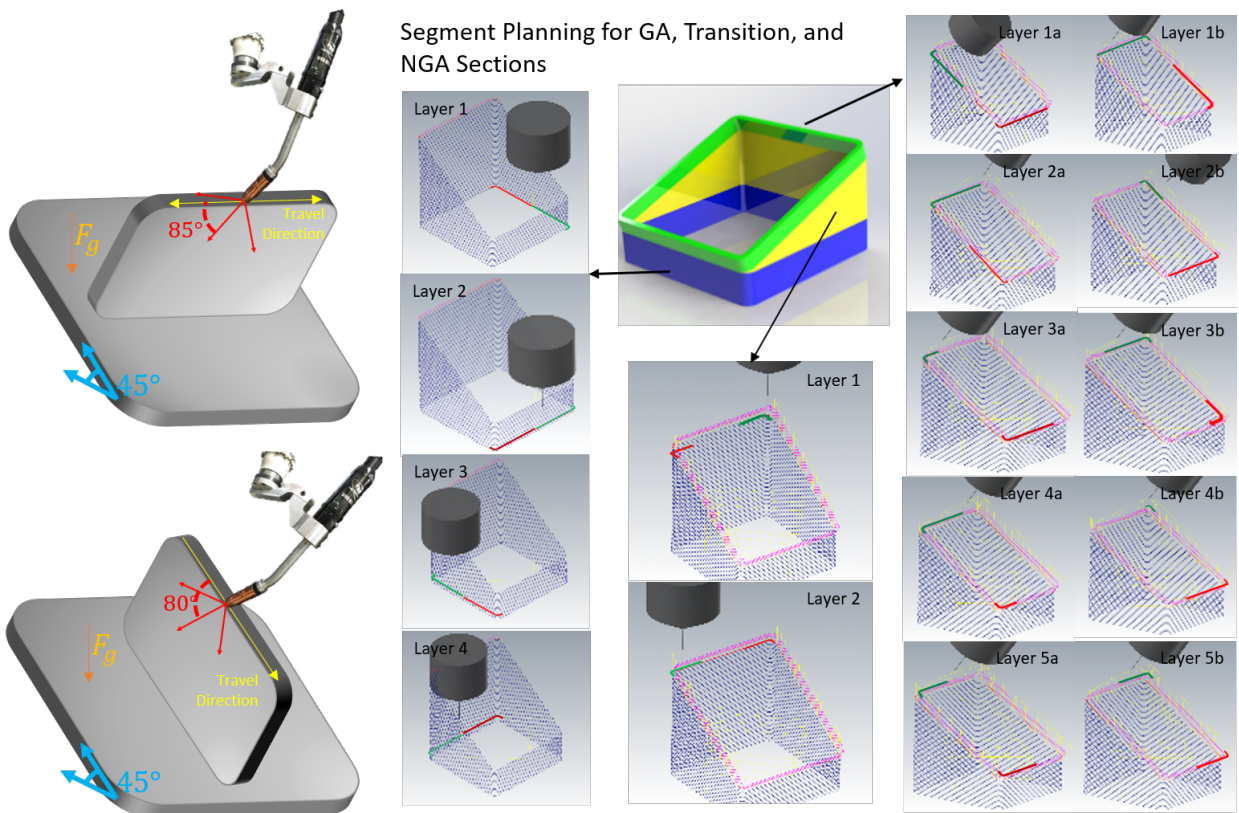


Figure 3.5: Initial methodology used for attempting the complex geometry and all of the steps to complete the build. This method delineated the horizontal and vertical NGA segments and was based on previous NGA experiments and planning experience.

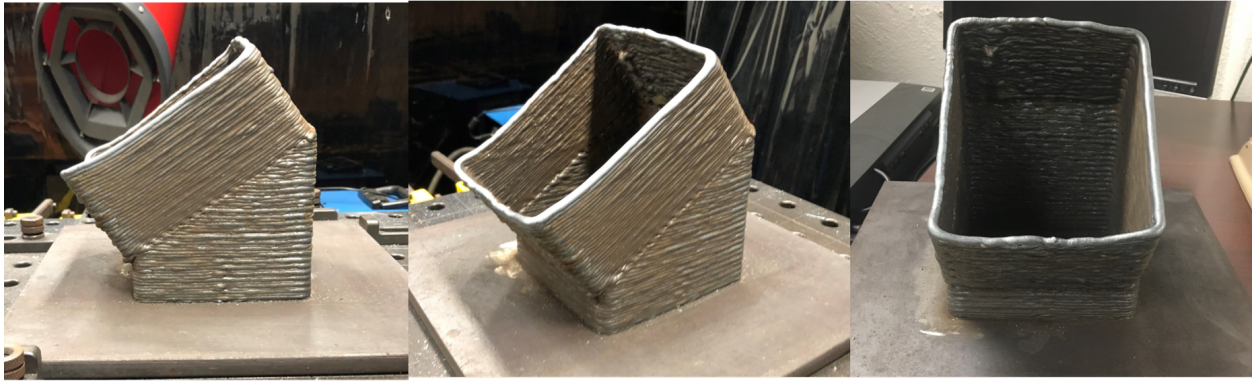


Figure 3.6: Final complex part geometry produced that completed the entire path plan. By choosing to handle the vertical and horizontal NGA segments with different path planning strategies and sequencing the NGA section properly allowed the full plan to complete, albeit with some near net shape issues.

NGA geometry is not perfect, there was success of improving NGA segments using simple heuristic relationships gleaned from experimental results. If the relationships for the vertical and horizontal NGA relationships can be established, future path planning can be improved using these relationships. Secondly, a new framework methodology from CAD to Part needs to be established that is robust enough to identify, correct, and simulate these planning changes. Third, the behavior of the NGA path planning is directly tied to process, geometry, and weld pool physics. Further delineation on the effectiveness of these techniques needs to be outlined to ensure that path planning can benefit from these techniques, and the degree to which these techniques could be successful for a given system.

The next step is to establish the effectiveness of NGA methods qualitatively and quantitatively, and to explore the limits of these using demonstration features. Establishing the quantitative effectiveness of simple NGA techniques will help with the development of the trajectory planning framework for NGA and full part features. It is also necessary to establish if these techniques introduce flaws to the deposited material.

Chapter 4

Feasibility of NGA Methods

The research presented in this chapter was the first attempt at establishing how effective NGA methods can be using heuristic methods. For this work, the main concern is with the final near net shape of the part when compared to the expected CAD. Therefore, researchers decided to use an Arctec Space Spider structured light scanner to build a point cloud of the surfaces for analysis. The scans were then turned into STL files using the Arctec Studio 14 software and imported into GOM Inspect for comparisons to the as expected CAD. The scanner is certified to have a resolution up to 0.1mm and 3D point accuracy of up to 0.05mm. Other demonstration parts were scanned using a FARO Scan Arm Quantum 3 blue light scanner located at the Manufacturing Demonstration Facility (MDF). The arm has a much higher resolution of 35 microns for the surface resolution. By bringing final part metrology into the analysis, researchers will be able to establish effectiveness on a quantitative scale, and use this information to improve and evaluate techniques.

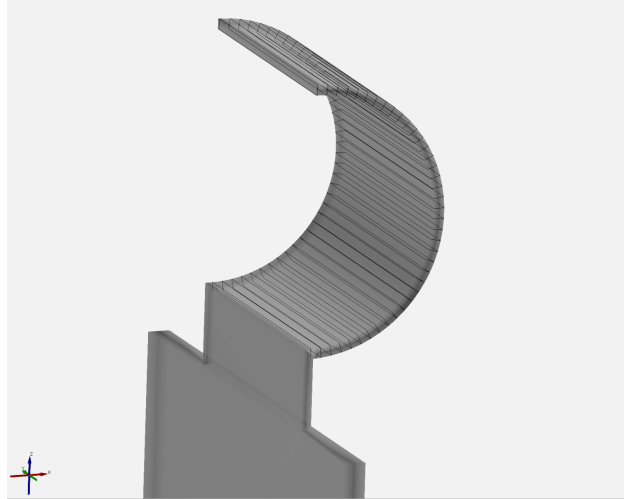
4.1 Updated CAD to Path Planning for Complex Horizontal overhang Geometry

For path plans to be correlated to the final deposited geometry required refinement on the planning stage. Manual programming of these paths was no longer sufficient due to time and accuracy constraints. Instead of slicing the geometries manually in CAD software, a

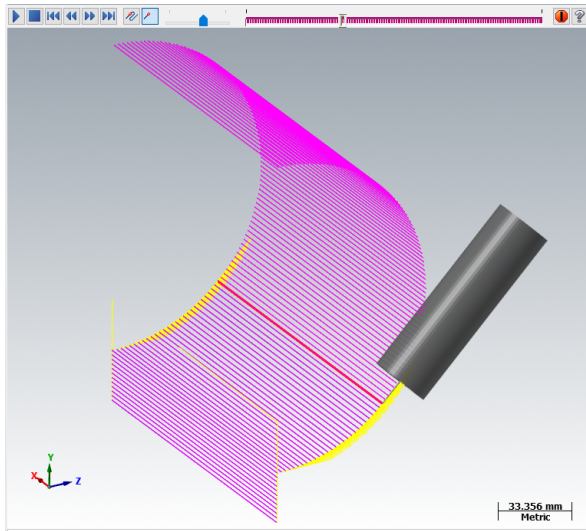
commercial metrology software GOM Inspect was used to take the geometry and develop slices from the expected CAD. Since the geometry from the CAD is used to develop these slices, the scanned as-built geometry can be correlated after deposition and scanning. Generating tool paths was still done with Mastercam due to a lack of commercial grade slicers having the flexibility to easily integrate NGA segments and low level trajectory changes [65]. The three basic stages of planning for each of the parts can be seen in Figure 4.1. Slices were generated from the contours of the surface in GOM Inspect (a), and then the initial direction and speeds of each layer were assigned in Mastercam (b). Finally, the path plan was imported into Octopuz (c). These trajectories were then exported from Octopuz as Kuka Robotics Language (KRL) for execution.

The approach of using 3 different types of software was necessary to ensure low level control of the torch orientation and position changes along the tool path. Typically Mastercam and Octopuz have operations for subtractive machining where the tool path planes are evenly spaced and the vector normal to the operation plane determines the Tool Center Point (TCP) orientation. For the NGA segments it is necessary to define multiple TCP orientations when considering curvilinear geometry with variable overhang angles.

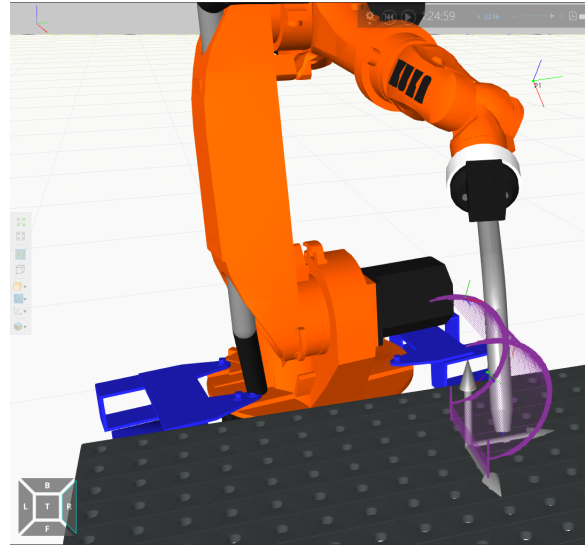
A few general assumptions were made given that the main interest is on the effectiveness of NGA methods. The first assumption is thin-wall geometry in the transverse direction. The thin-wall is not only for simplification of planning, but also to be able to see transient or steady state effects of any trajectory planning techniques. A layer height of 2.25mm and layer width of 6mm was adopted from the previous layer experiments with the same welding settings. The initial rail and segments can be defined using the relationship shown in Figure 4.2. Each layer alternates directions, implying that the starts and stops also alternated on each edge of the part to help account for the bead height and thermal effects[14]. By keeping process settings constant, the full effect of modulating the torch can be seen without also introducing changes due to process settings.



(a) GOM Inspect



(b) Mastercam



(c) Octopuz

Figure 4.1: The three different commercial software used to generate the slices and resulting path plan necessary for NGA demonstration builds.

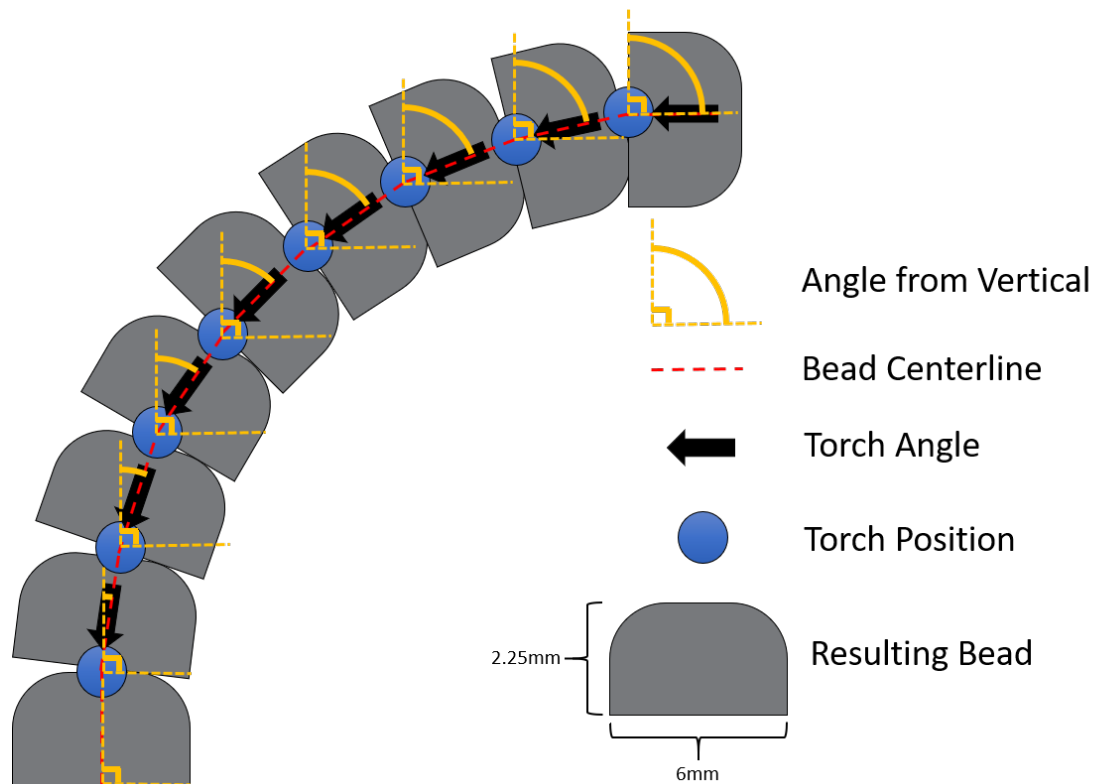


Figure 4.2: Simplified definition on how the slices are defined for the rails for the single bead walls and the cylinder parts. All torch orientations are aligned with the center line of the bead to the previous bead. The walls and cylinder parts used similar bead and rail approximations.

4.2 Horizontal overhang Walls

Given the initial success of the Complex Part build from Figure 3.6, it was decided to focus on trying to establish the effectiveness of the horizontal NGA techniques. These segments are easier to isolate and observe trajectory planning effects since they are completely unsupported while ensuring that the torch does not interfere with growing geometry features. The goal of these experiments was to determine the upper limit of overhang angle and provide a control for testing other NGA methods. The walls were built to have a GA section 42 layers long with an NGA section that was also 42 layers long. The NGA section was built with the torch angle perpendicular to the previous layer, meaning that if the NGA section was labeled 35° that the torch angle was also 35°. The walls were built with two parts on the same substrate so that there was minimal welding downtime - eg. 35° overhang was being welded on while 45° overhang was cooling¹. Overhang angles 35°, 45°, 55°, 65°, 75°, 85°, 95°, and 105° were completed for this analysis.

An overview of the results of the builds can be seen in Figure 4.3. Viewing the results, it can be seen that as the overhang angle increases, the bottom of the NGA segment surface roughness increases. It can be seen conversely on the top surfaces as under-filling near the edges. The top surfaces generally look much better at reaching near net shape than the bottom surfaces.

The CAD models for these walls were compared to the as-built to determine the build's deviation from nominal CAD dimensions and resultant near net shape. Using GOM inspect, a deviation map can be generated from the meshes and projected onto the scanned surface map to get an idea of the deviated surface. The green represents nominal while red or blue indicates over fill or under fill of the actual surface with respect to the CAD. A summary of deviation maps of the overhang walls can be found in Appendix A. The data from these deviation maps can then be used for further analysis by exporting the deviation map values.

A quantitative value of the surface deviation calculation on the top and bottom surfaces is needed to see the relative trends with near net shape for the overhang demonstrations. The deviation map data was pulled from the aligned metrology scans and then compared

¹Example video of the Mastercam plan can be seen here: https://youtu.be/VYHuJ2Ss_bU

Overhang Demonstration Results

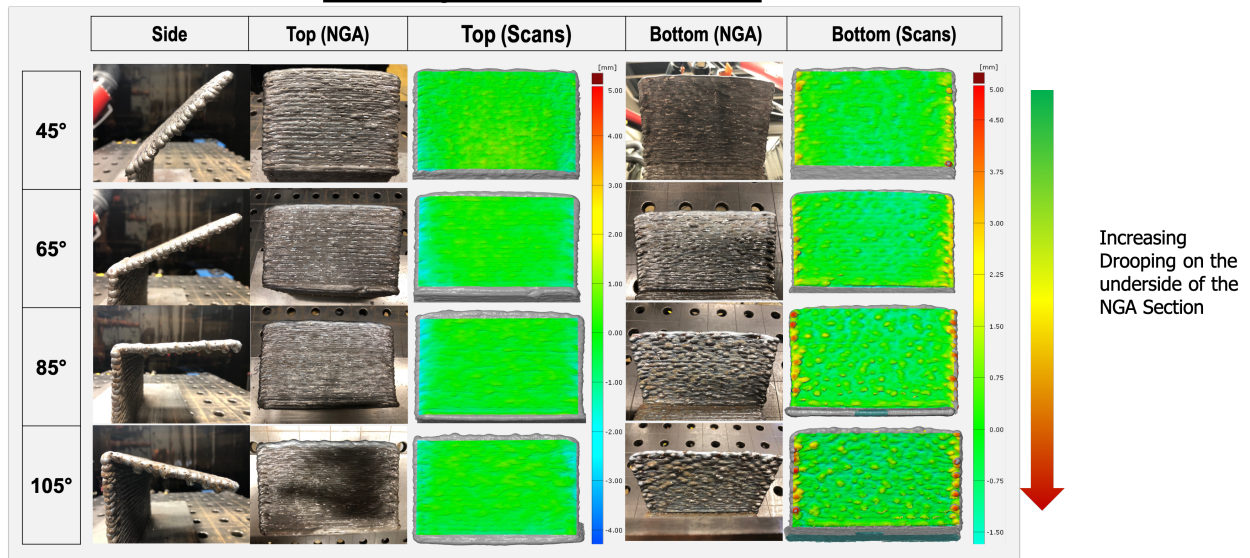


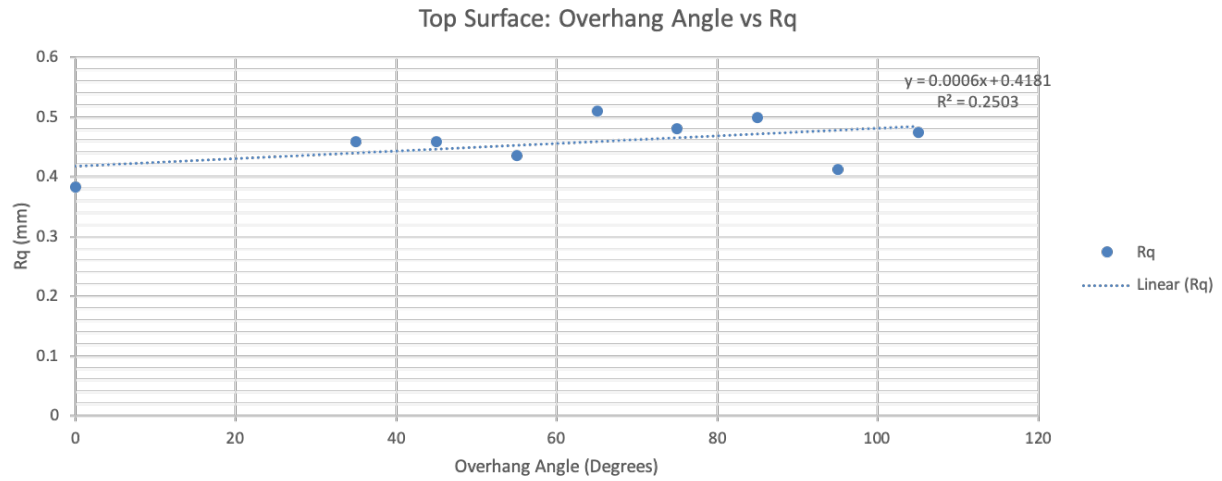
Figure 4.3: The results of a few different wall overhang angles and particular views beside the scans of the top and bottom surfaces.

based on overhang angle as seen in Figure 4.4. The calculation used for the quantitative analysis is defined in eq. (4.1).

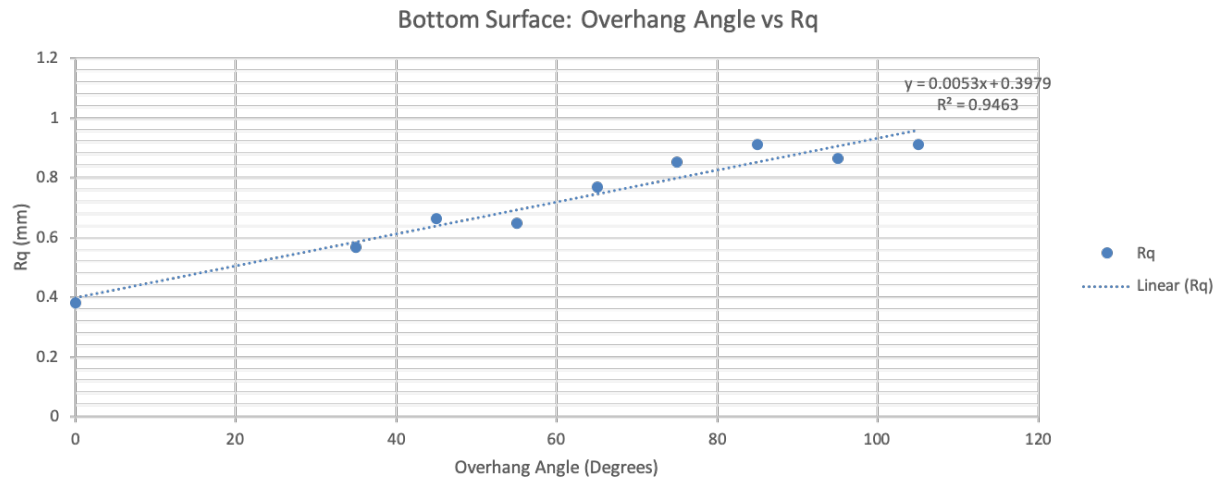
$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n y_i^2} \quad (4.1)$$

Equation (4.1) is taken from [62] for standard surface roughness metrics. R_q is known as the root mean square surface roughness metric where n is the sample number and y_i is the deviation value taken from the surface scans. A single value representing each top and bottom surface R_q value was found from the data and plotted alongside the planned overhang angle.

Figure 4.4 shows all of the plotted deviation surface roughness calculations with the corresponding overhang angle. As can be seen from the deviation trend line, there exists a highly linear relationship to the surface roughness (R^2 of 0.9463) increase from the overhang angle for the bottom surface. The top surface does not seem to show correlation to overhang angle (R^2 of 0.2503), and in fact the maximum surface roughness difference from the GA section (seen on the far left) is .11mm which falls close to the uncertainty of the scanner that was used for this analysis. While the current planning method is effective for achieving the overhang top surface, more work will be needed to refine the bottom surface roughness. The maximum bottom surface deviation is also less than 1mm of surface roughness difference for 105° of overhang. 1mm of surface roughness is not significant because it is less than 20% of the desired bead width (6mm), from which these R_q deviation measurements are taken. With a less than 1mm surface roughness for the bottom segments, it was determined that for isolated NGA segments of up to 105° that a torch position shift was not necessary, and that orienting the angle perpendicular to the NGA segments for multiple single wall layers was more than acceptable for the steady state growth of NGA segments. While near net shape seems to have been reached using the simple perpendicular torch rotation, it needs to be ensured that resultant material properties were not affected by the torch orientation.



(a) Top Surface Deviation



(b) Bottom Surface Deviation

Figure 4.4: The results of the surface comparison for both the top and bottom surface in terms of the overhang angle and Rq (RMS) value. The top surface can be seen to be relatively smooth while the bottom surface shows a linear trend indicating increasing surface roughness with increased overhang angle.

4.3 NGA Wall Section Strength

To ensure that the chosen process settings and NGA methods do not significantly affect overall material properties, new thin walls were printed that used identical process settings but had longer overhang segments to allow ASTM standard E8 tensile samples to be taken from the overhang sections. A 50° and 70° wall were printed, and tensile specimens were taken along the build direction. These tensile samples were loaded into an MTS C45 electromechanical test system and tensile testing was done on 5 samples from each of the overhang walls. The results can be seen in Figure 4.5. The graphs show the plots of the 5 samples and then average tensile strength of the 50° and 70° overhang. The average tensile strength found through tensile testing is 98% and 96% of the minimum expected tensile strength of this material's as-welded condition. However, this is somewhat expected due to the thermal cycling differences of WAAM and welding. The heat cycles due to AM techniques result in the yield strength decreasing while ductility is increasing. However, given the differences from welding to WAAM, the fact that the measured tensile strength is within 4% of the expected as-welded condition for a significant overhang angle indicates that the process settings and NGA techniques used to manufacture these walls are acceptable for continuing analysis on the near net shape of the part.

The overall strength of the overhang sections indicate that keeping the process settings consistent within acceptable ranges will allow NGA segments to be built more consistently and effectively for manufacturing. The result is significant as it helps support the claim that introducing non-process related changes to help extend the capabilities of an AM system to complete more complex geometry is possible with NGA methods and more complex path planning. The implication is that a combination of better process related changes and more complex trajectory planning could be the key to unlocking true 3D printing techniques for LSAMM.

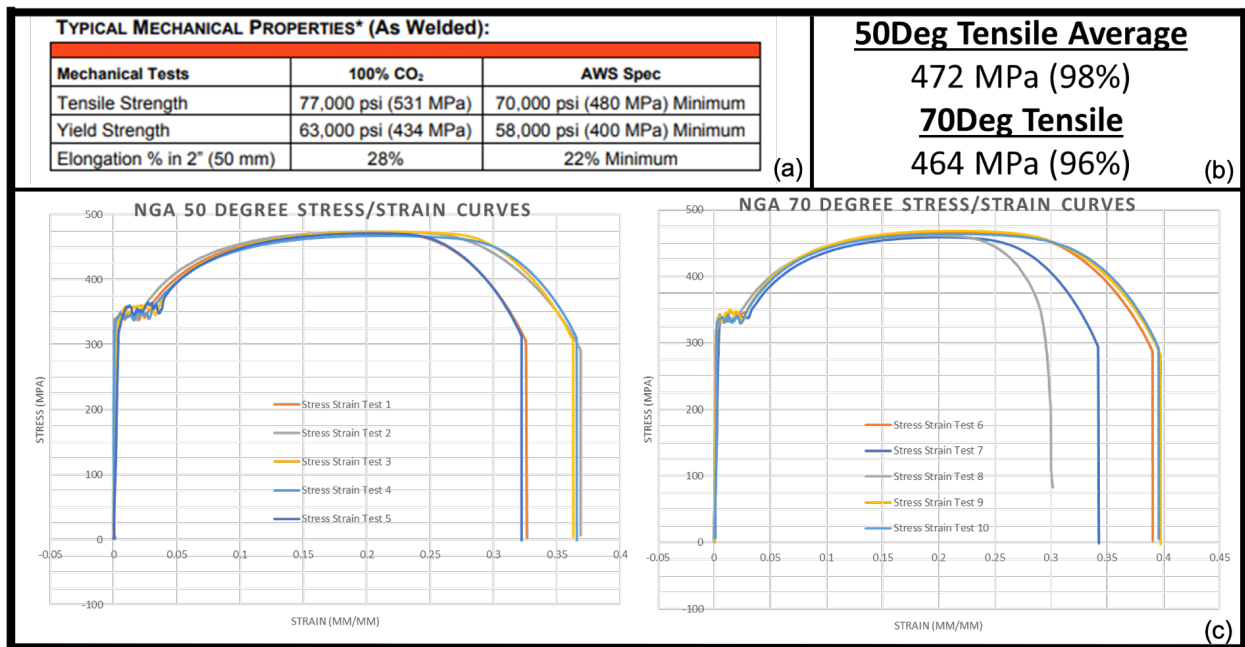


Figure 4.5: (a) The as-welded mechanical properties of ER70S-3 Wire[36]. (b) The average of 5 samples for the tensile strength measured from samples and the percentage from the as-welded. (c) The resultant stress strain curves taken from the 5 samples for a 50 degree and 70 degree wall section.

4.4 NGA Case Studies

The results from the horizontal overhang walls show that for thin wall overhang sections the methodology used to create NGA segments is effective. Therefore, experiments were done to extend this to variably changing overhang segments (curvilinear) in preparation for applying these techniques to a more complex geometry. These parts were used to demonstrate a part with NGA layers that contained a $\pm 90^\circ$ layers, and with the Full Cylinder containing an enclosed top segment.

4.4.1 Half Cylinder Welded Part

The Half Cylinder was planned to be 6 inches long in the transverse direction, while having a radius of 6 inches and a 12 layer raft (initial wall) to ensure the thermal equilibrium was reached before starting the NGA segments. A wait time of 30 seconds was used between layers to give enough time for the part to cool before starting the next layer². The final 119 layer build took around 2 hours to complete with start stops to clean the spatter from inside the weld cup and ensure the wire was clipped and clean³.

As-printed Half Circle

The as deposited part can be seen in fig. 4.6. It is seen that the start stops of the layers typically have the furthest deviation from a steady state middle surface. The surface waviness seems significant on the underside of the top and bottom parts of the NGA segments - similar to the effect we have seen with the overhang walls.

Half Circle Metrology

The metrology of the full part can be seen below in Figure 4.7. The scanner indicates a resolution of 35 microns for these scales, but decimation of the surface to reduce data memory requirements and comparison were performed to visualize the part with the deviation map.

²Example video of the Mastercam plan can be seen here: https://youtu.be/tOYDkVC_biI

³A full video of the Half Cylinder can be seen here: <https://youtu.be/pjVJ-T29yDU>



(a) Isometric View

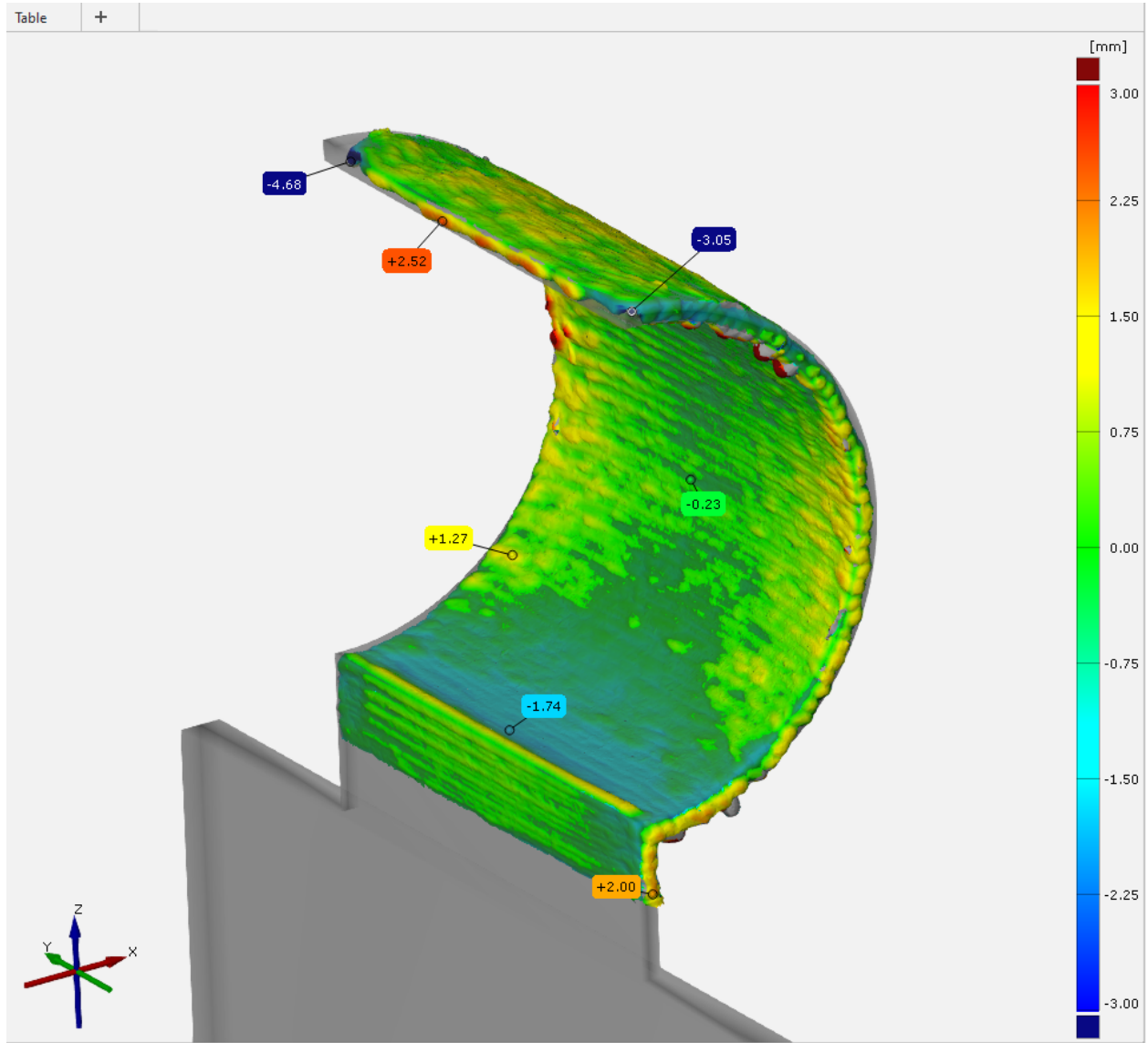


(b) Side View



(c) Back View

Figure 4.6: as-printed condition of half circle shape.



(a) Isometric View

Figure 4.7: 3D scans of as-printed half cylinder shape used to check geometric tolerance as compared to original CAD model and deviation map projected onto the surface.

The maximum deviation is on the edge and is about 5mm. This is still less than one expected bead width and is a point where the surface tension of the weld pool was lost and dripped. This did not seem to effect the overall part success and plan. Viewing the last welded layer it can be seen that the part actually extended further than the expected CAD - meaning the NGA segments were completed successfully throughout the sweep of the NGA angles. Initial layers of the NGA portion started off too low, but as the part was built the part recovers its near net shape and approaches the expected CAD geometry. The center of the part, which is where the bead would have been at a steady state, is very close to the expected CAD while the edges where the starts/stops occurred had the most significant deviation (4.5mm).

Therefore, for a variably changing overhang angle, the desired near net shape was achieved for the steady state part of the geometry with minimal open loop planning changes. Considering the only change to the path plan was to apply a perpendicular torch rotation to each overhang segment, the NGA methods seem effective for variably complex parts with significant amount of overhangs with this process and welding settings. Also, the deviation at worst was still less than a bead height/width for the edges where the welding process is not at a steady state. The next step is to build a fully enclosed cylinder with similar NGA techniques and path planning.

4.4.2 Full Cylinder Planning Changes

The Half Cylinder geometry does not contain features like the geometry generalized in Figure 2.4 where the torch would interfere with the as deposited geometry if the orientation of the torch does not change. Since the top of the part plan would intersect on itself, it would be physically impossible to keep the torch perpendicular to the previous layer without obstructing the opposite side. Now one of the few options left is to introduce a position shift along the deposition line or process changes to influence the weld bead to fall into the desired location with a less than ideal torch orientation. Therefore, a few different experiments were designed and executed to determine a better position and orientation correction to allow the enclosing overhang segments to finish building for the full cylinder. An isometric view of

these experimental enclosing sections can be seen in Figure 4.8 and the corresponding side view in Figure 4.9.

Enclosing overhang Segments

To simulate the enclosing section, a top third of the part was completed, minus the top 20 layers, using perpendicular torch methods. The remaining enclosing layers were attempted using three methods, as shown in Figure 4.8. For the first attempt, once the torch reached the top interference layers, the torch angle would be increased every layer just enough to prevent torch clipping. However, the increased torch angles resulted in the layers building up vertically until the path interfered with the front of the torch and the weld had to be stopped. The layer build up can be seen in Figure 4.9(a).

To prevent layer build up, layer shifts with a vertical torch orientation were used in the second method. A simple experiment was performed to determine the optimal shift distance. After reaching the first interference layer on the top third of the cylinder section, a single bead placed above the last bead with a GA orientation was deposited. The start and end of this single bead was incremented a total of 2.25 mm across the center line to help approximate a "shift" along the path necessary to achieve a desirable bead shape with a non-optimal torch angle. A diagram of this experiment is shown in Figure 4.10.

After the single bead experiment was completed, the resultant shape was examined manually and a distance measured at the location where the single bead fell into place as if it were deposited with an optimal torch angle. This location was triangulated as having a 2.125mm shift towards the center of the enclosed section. The enclosing layers of the top cylinder section were then printed using this as the shift distance value and a GA torch angle for each layer, as shown in Figure 4.8(b). During the deposition of this section the wire would sometimes miss contacting the last layer and would arc with the build plate before reestablishing the arc on the deposited geometry. This resulted in the edges where the stop/starts are located being under built.

The final enclosing method attempted combined both of the first two methods: 2.125mm position shift and modulating the torch angle to prevent interference, as illustrated in Figure 4.11. This method gave the best results of the three, with the angled torch insuring



(a) Angle Shifts Only

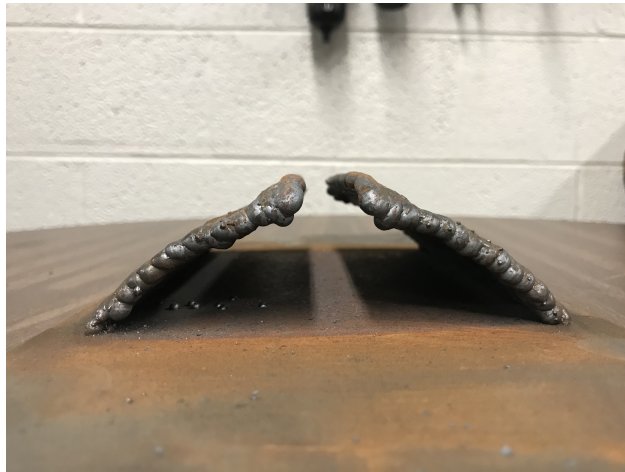


(b) GA with Position Shifts



(c) Angle Shifts and Position Shifts

Figure 4.8: Cylinder top sections using different enclosing methods.



(a) Angle Shifts Only



(b) GA with Position Shifts



(c) Angle Shifts and Position Shifts

Figure 4.9: Side views of cylinder top sections using different enclosing methods.

wire contact with the part and the position shifts preventing layer build up, as seen in Figure 4.8(c) and Figure 4.9(c). For the very last layer, a weaving weld pattern was attempted, but the resulting arch connection was not smooth and resulted in some overbuild. Because the angle shift and position shift enclosing method gave the best result, this method was used for the final path plan of the full cylinder part.

As-printed Full Cylinder

The final build of the enclosed cylinder contained 224 layers and took about 2.5 hours to complete. Only the initial raft and first 2 layers of NGA on the bottom of the part required a wait between layers, as there were two completely different NGA segments being built simultaneously⁴. The demonstration part was deposited without any issues, including the enclosed section on the top of the cylinder section⁵.

The as-built full cylinder can be seen in Figure 4.12. The shifted section is not deposited as consistently as the bottom section, but the entire build was completed successfully. The layers are fairly consistent for both sides, with only the last layer deviating greatly from the curvilinear shape of the cylinder. Observing the side view, it can be seen that one side of the enclosed section drops lower than the other section when compared to a half cylinder. The final enclosed section layer is taller than it should be relative to the flat enclosed final layer in the expected CAD.

Full Cylinder Metrology

A full view of the full cylinder metrology can be seen in Figure 4.13. The full part metrology is very similar to the half circle when it comes to the sides of the rounded sections. The part is very close to nominal on the sides and only has deviation from the expected CAD in the greatest angle overhang sections near the top and bottom of the part. Even with the top few layers and a few drooping sections, there are no part deviations greater than 6mm.

⁴For a full view of the path plan for the Mastercam plan: <https://youtu.be/wD7eMzedFvM>

⁵For a video of the full build: <https://youtu.be/5Pd9koZEEwo>

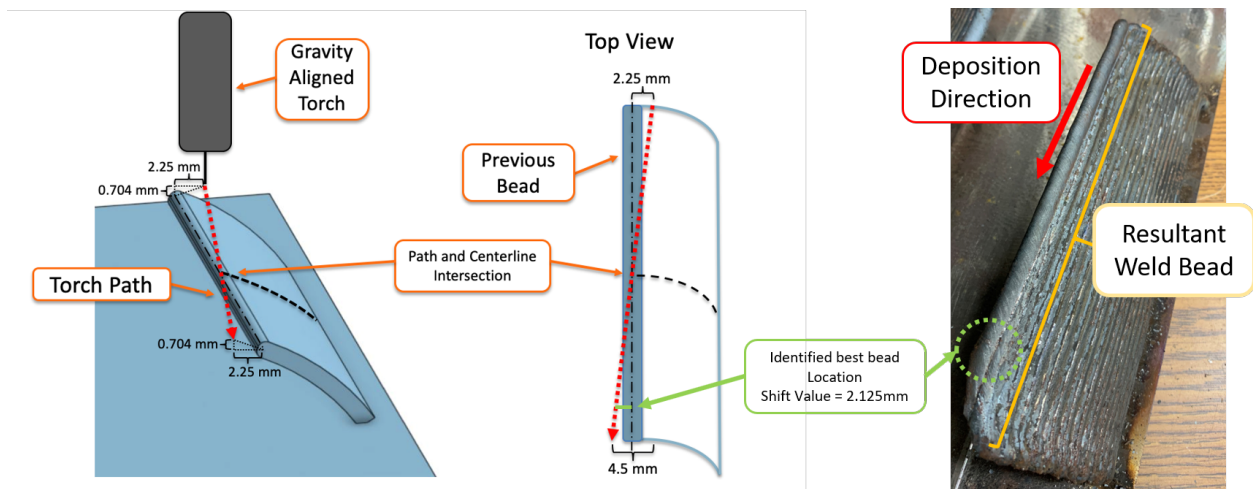


Figure 4.10: Simplified diagram showing the test to determine the correct "shift" parameter for a path from the first layer where the torch would interfere with the opposite NGA segment. A deviation of one bead height from left to right was completed and the resultant bead measured by hand to determine the appropriate shift for the remaining NGA layers.

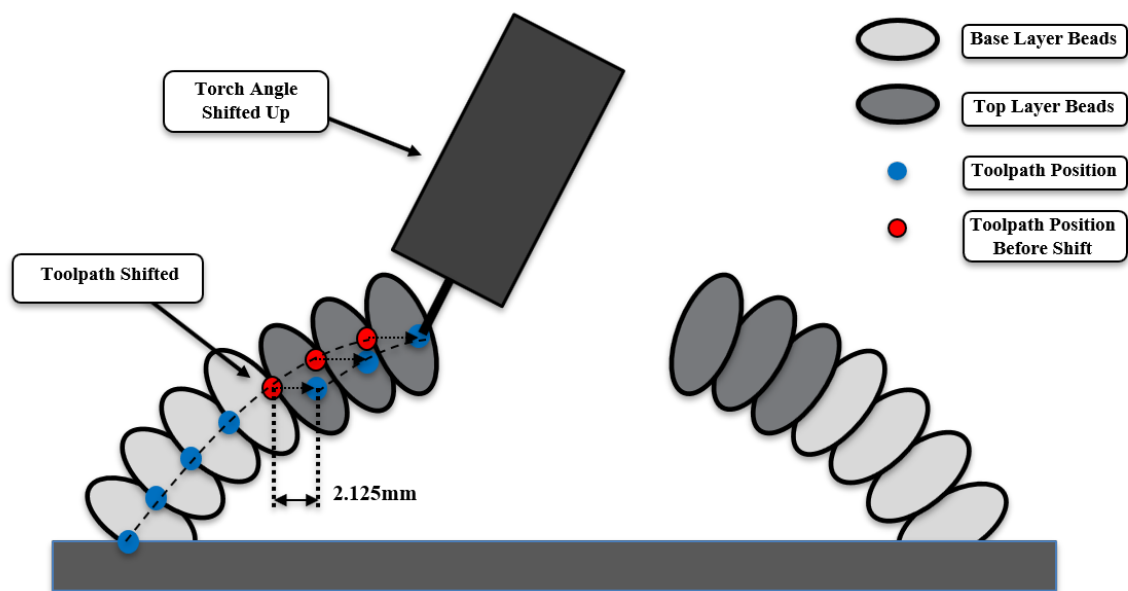


Figure 4.11: A diagram showing how the final part plan was shifted to be able to complete the enclosing section for the top of the full cylinder by shifting 2.125mm towards the center of the part for the final 20 layers.



(a) Isometric View

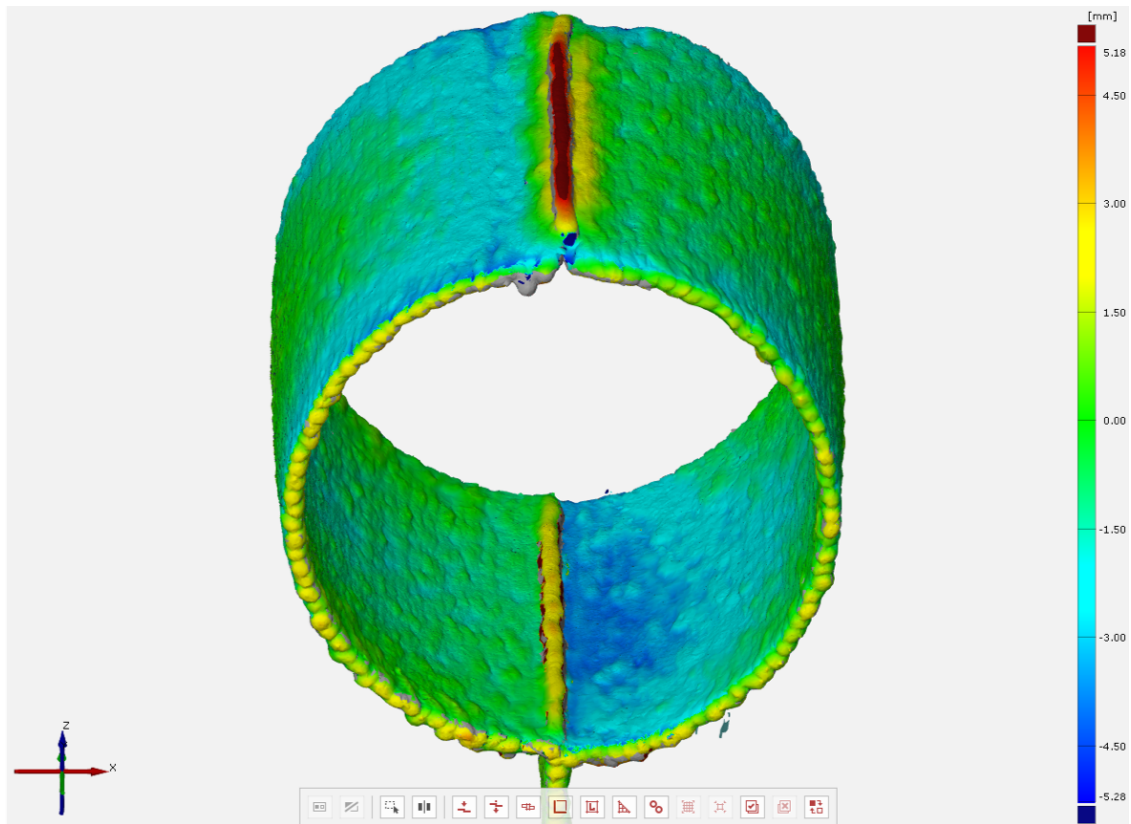


(b) Side View



(c) Back View

Figure 4.12: as-printed condition of the full cylinder geometry.



(a) Isometric View

Figure 4.13: 3D scans of as-printed full cylinder shape used to check geometric tolerance as compared to original CAD model and deviation map projected onto the surface.

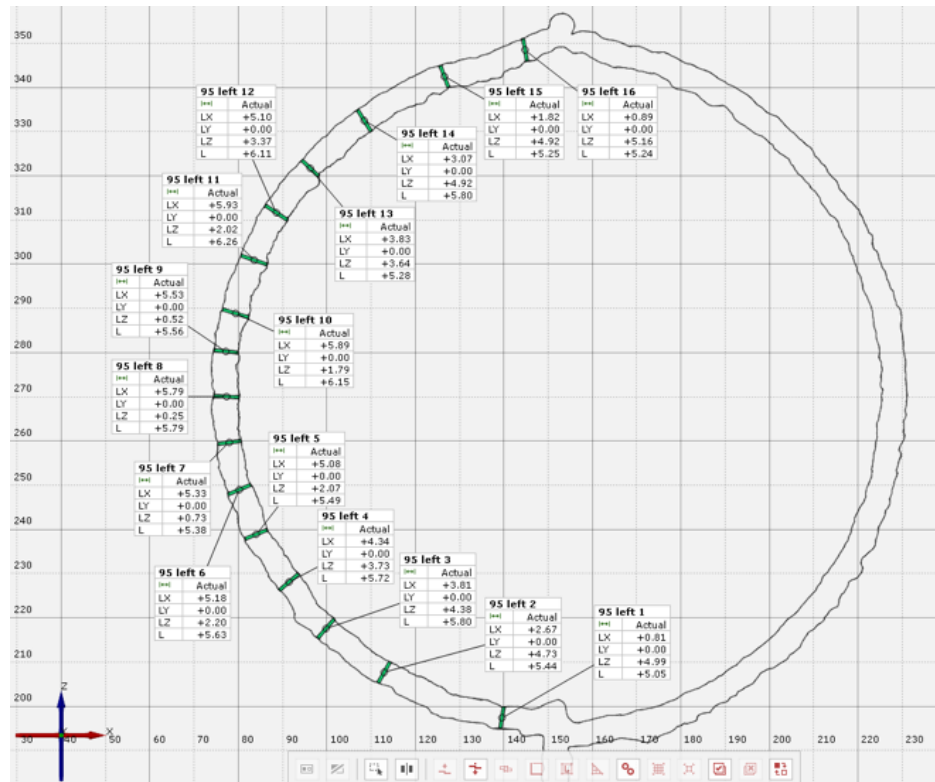
Further Full Cylinder Feature Analysis

Since surface roughness calculations would be tougher to characterize with an already rounded surface, researchers wanted to double check that the resultant bead size throughout the part was relatively consistent, particularly in the steady state NGA section of the cylinder section (middle). The main indicator of success would be the change of the bead width across any section of the full cylinder. If the bead width was consistent across all sections, the NGA methods of shift and rotation can be qualified as techniques to help improve near net shape for overhang sections. Cross sections of the cylinder along the transverse direction were created within the GOM Inspect software, and measurements of the scanned bead widths can be seen in Figure 4.14.

While the expected bead width was 6mm, the plotted values show that throughout this cross section that the expected bead stays slightly below the expected size. However, it deviates no more than plus or minus 1mm from the expected 6mm width, meaning that the NGA beads are behaving similarly to a GA deposited section, but slightly smaller due to the effects of the surface roughness. However, the general representation of the rail sections with expected bead width and height for the open loop path planning still allowed a deviation of bead width less than 1mm, even for the sections that were shifted near the top of the part with a less than desired torch angle. The analysis of the bead width shows that with a proper application of torch shift and rotation, overhang sections can reach an acceptable near net shape without having to modify process settings throughout the build.

As mentioned from the pictures of the full cylinder, lack of symmetry with the very top and bottom of the part needs to be examined more closely. As seen from Figure 4.14, the enclosed top section and the bottom section where the NGA sections begin from the raft seem to have the greatest deviation from the expected CAD. An expanded view with measurements can be seen in Figure 4.15.

Viewing Figure 4.15(b) identifies interesting phenomena. While the path plan assumes that the bead would be deposited 90 degrees perpendicular to the wall, it does not explain the right side base offset seen as the full cylinder begins its first few layers of NGA. There is a significant height difference on these first layers even though the plan does not reflect

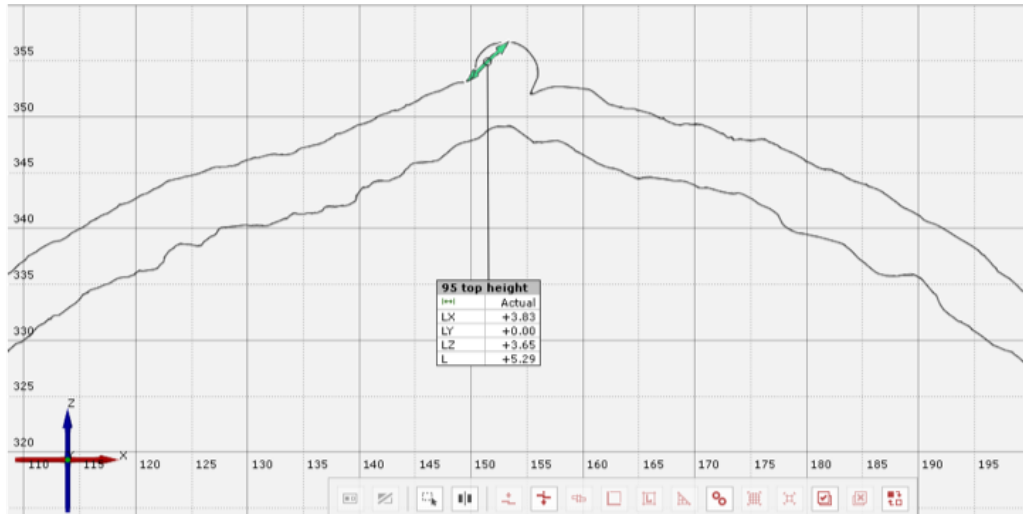


(a) Full Cross Section

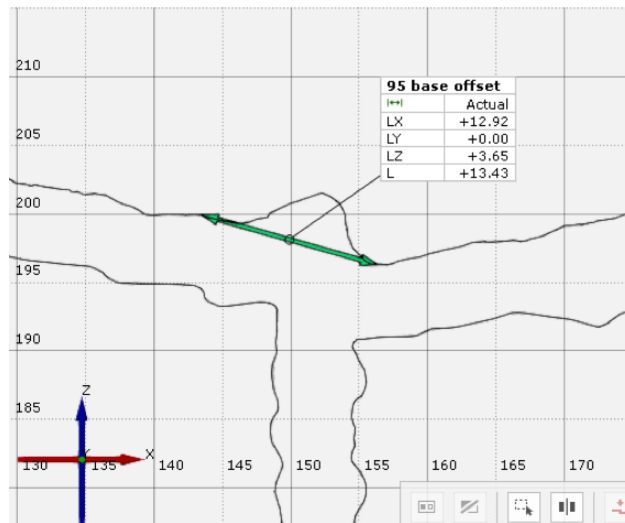


(b) Measured Bead Widths

Figure 4.14: The results of measurements of bead width in a cross section taken 95mm through the part and a graph of the measured beads.



(a) Top Section



(b) Bottom Section

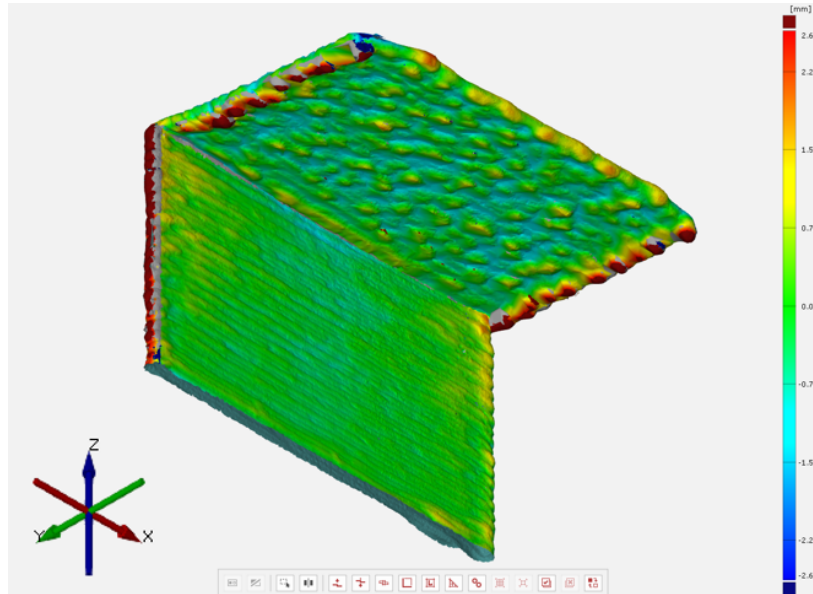
Figure 4.15: Cross sections of the top and bottom of the geometry showing the outlines of the surface within the transient segments of the build.

these changes. This is also the same effect observed from the deviation map generated from the CAD from Figure 4.13. The right side is blue, indicating it is under filled as compared to the left side of the base with respect to the CAD. Given that the right side is lower and the left side is higher, the analysis indicates that wire curvature at steep torch angles caused the beginning of the NGA sections to not align to the beginning raft. Due to low arc forces associated with RMD and short circuit waveform, any curvature of the wire could shift the desired path off of the planned path. Considering the change is 3.65mm in the Z direction means that these layers are offset by more than a layer height, which is not conducive for achieving near net shape.

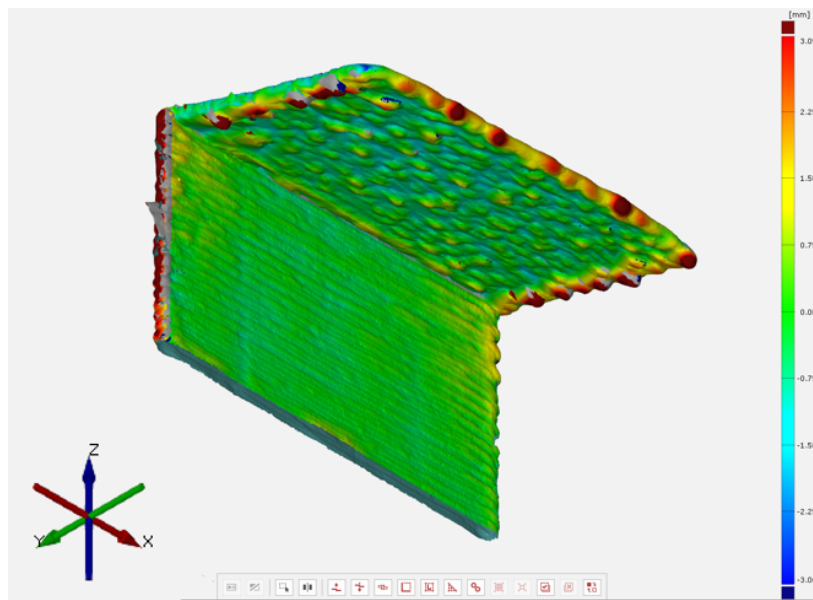
Observing the top section in Figure 4.15(a), a similar effect is seen in the opposite side. As a result, when the top 20 layers were shifted there was a slight change to the weld pool width, but now the left side of the cylinder is lower than expected while the right side matches up to the net shape geometry. Although the last layer did not fully penetrate, both sections did end up meeting and joining in the middle - indicating that the path planning for the build was correct. Therefore, analyzing the top section provides more evidence that the curvature of the wire is responsible for slight deviations, particularly with the steep torch angles associated with large overhang layers.

This theory is supported by observing the shifted section cross section on top of the part on the left of Figure 4.15. The left side of the top part would have a similar torch orientation to the bottom right section due to the perpendicular planning of the torch, while the right side of the top and the left side of the bottom would have similar torch orientations. It is likely that the wire curves downward while oriented towards the -X direction in Figure 4.15, and when it flips over the wire curves upward when oriented in the same direction as +X.

The implications for NGA methods mean that a greater level of real time control of the process is necessary for ensuring stability. If the as deposited bead is affected this significantly by wire curvature, real time control of layer height or bead deposition is necessary to ensure that the effects of the NGA open loop planning can be delineated from other welding process effects. These small process inconsistencies, while significant for single bead geometries, are on the order of magnitude of single layer heights and still produced bead widths less than 1mm from nominal. So, these techniques can be applied to a multi-bead structure to test



(a) 95 Degree NGA Wall



(b) 105 Degree NGA Wall

Figure 4.16: Underside view of the 95° and 105° overhang walls showing that the bottom intersection of the GA and NGA segment has minimal deviations from the expected CAD.

their effectiveness at extending a more complex system’s capability of successfully depositing overhang sections.

4.5 Conclusions from Half and Full Cylinder

The goal of this research was to demonstrate that building NGA segments with constant process settings by reorienting and re-positioning the torch was possible, instead of relying on changing the process parameters [68]. The walls and cylinder demonstration parts show that it is possible to keep the welding process settings constant and use the inherent arc forces to achieve desired bead geometry and placement. Applying a torch rotation and shift along the desired part contour allowed NGA segments with up to 105° of overhang to be completed, as well as fully enclosing segments by applying a torch shift. The conclusions from these experiments is that:

- Using only torch rotation can improve overhang near net shape vs. GA techniques, but results in the underside surface having a significant increase in surface roughness
- While the robot position is very accurate, a small difference in the rotation and tip calibration (due to wire curvature) can result in beads having significant placement differences
- Future works must focus on mapping the ideal torch rotation and shift for different materials, systems, and geometry features to provide a robust path planning solution for true 3D printing

The results from this chapter indicate that NGA methods can be used to help improve deposition of overhangs and more complex geometries. The methods will allow more simple path planning of geometrical features based on torch rotation and shift. The first step is to define how the NGA methods can be implemented in the path planning stage. After defining NGA methods for path planning, simple experiments can be used to help dictate the ideal torch angle and shift for certain overhang feature types which can then be applied to geometry for improving final near net shape.

Chapter 5

Novel Framework for Additive Manufacturing

Given the results from Chapter 4, it can be seen that adopting NGA torch strategies can significantly increase the capabilities of a DED system to complete overhangs, including enclosing segments like the one seen in the Full Cylinder geometry. Layer-based approaches to generating AM paths make a host of assumptions which affect the printing process and final part. For example, the tessellation of the curved surfaces of a CAD model represented as an STL file causes imprecision in the representation of curvature. Additionally, separating a part representation into 2.5D layers means that geometry outside of the slice plane is subject to the stair-step effect [58], which decreases the accuracy of the printed part. Chapter 5 will generally outline how NGA methods will be defined in the scope of a path planning framework for WAAM. The framework was conceptualized and developed in MATLAB and used to plan and execute highly complex geometrical features on the welding cell at the University of Tennessee.

5.1 CAD to Path Framework Idealization

Commercially available slicing software does not offer low-level control over WAAM process parameters and seldom offers capabilities to control the orientation of the deposition head. By considering a novel framework for organizing print system trajectory data for an AM

build, it is possible to easily control low level process parameters such as print travel speed and tool orientation, and to rapidly generate robot programs with minimal operator input. An overall view of the conceptualized path planning framework for this research can be seen in Figure 5.1.

Taking this trajectory framework and implementing the NGA rotations and techniques is of vital importance for ensuring path plans are executed properly. The goal of this framework will be to allow a path planner to easily and quickly generate trajectories based on given "slices". While this framework does not include slicing of the geometry, by using GOM Inspect or commercial slicers, this path planner can then be used to implement the required torch rotation and positional changes for NGA methods. Future algorithmic planning can also be automated with the framework by properly segmenting and organizing segments.

5.2 Trajectory Planning Framework

The trajectories used in the AM build will be organized in a five-tier information hierarchy. In order, from lowest to highest level, these elements are: waypoint, move, contour, segment, and part. Following this scheme, a part consists of segments, a segment consists of contours, a contour consists of moves, and a move is made up of two waypoints. The contents of each of these elements is shown in Figure 5.2. The arrangement of data allows the user to make changes to the path plan at intuitive levels of abstraction. For example, when using this framework to plan NGA builds, certain algorithms can be applied to only NGA segments, or to moves that are co-linear.

Waypoints were designed to contain the instantaneous information necessary to control the motion of the print system. This includes the position and orientation of the deposition head, as well as the travel speed. Additional process parameters, such as welding settings, are currently encoded at the part level for consistency, but could be included at this tier. All of the information contained within a waypoint can be presented directly to the robot controller, which will execute the weld with the given instructions.

Moves consist of two points: a start point, and a stop point. This arrangement is important for two reasons. First, a move geometrically defines a continuous, straight line in

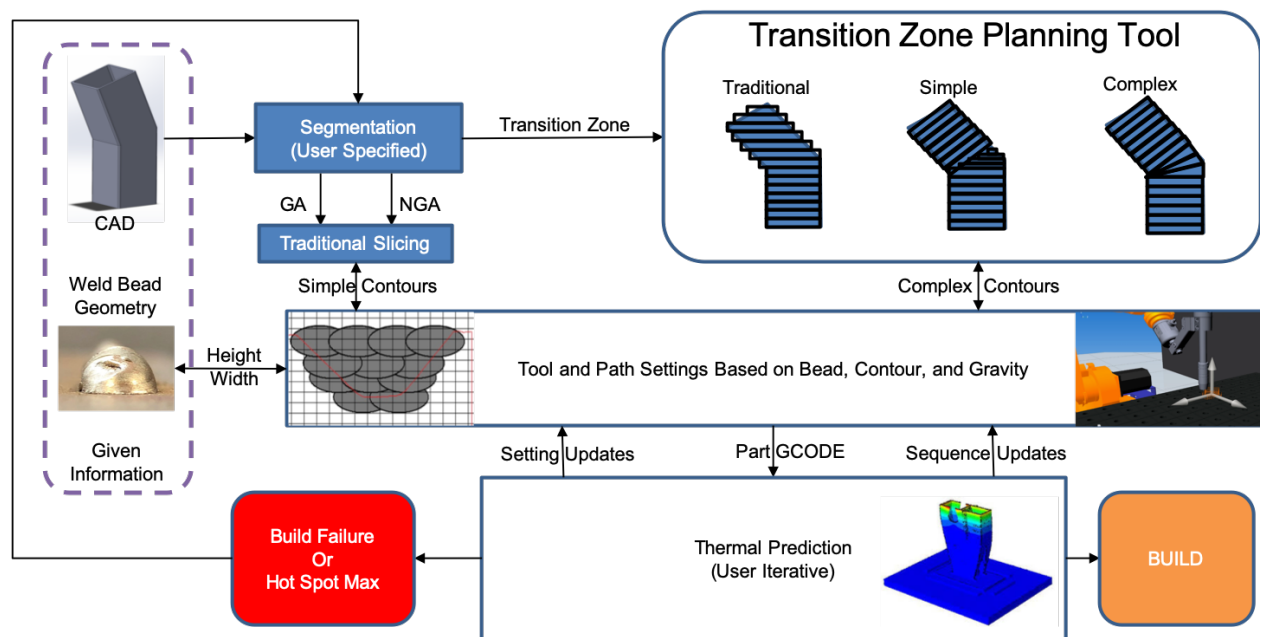


Figure 5.1: Generalized Framework and the implementation of these segments.

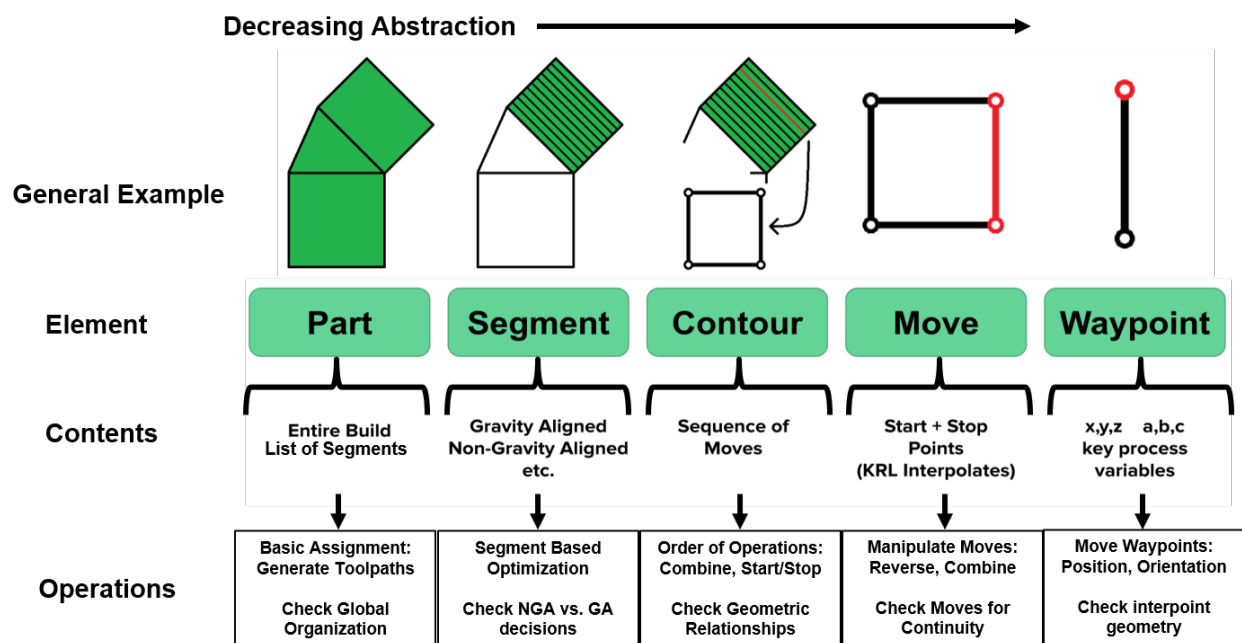


Figure 5.2: Framework for 3D AM Build Data

space along which a bead will be printed. Observing the start and stop points of a given move defines the travel direction vector along that move. Comparing the start and stop points of two moves can indicate whether the moves are co-linear, and whether sequential moves are continuous (i.e. connected start-to-end). Second, the KUKA robot controller used in the experimental validation interpolates process parameters between any two given points. Thus, a move provides a representation of the process between two points.

Contours are defined as a series of continuous moves. In traditional 2.5D printing, contours are similar to a layer. The moves within a contour are executed in order without stopping deposition. Within this framework contours are not required to be planar, or necessarily evenly spaced in any direction. Build instructions such as tool retracts, robot re-orientations, and pauses are inserted between contours.

Segments contain a sequence of contours, and can be classified based on the macroscopic geometry of that section of the part. For example, a segment may be classified as Gravity Aligned (GA), Non-Gravity Aligned (NGA) or transition (between GA and NGA). This categorization allows for path planning software to conditionally manipulate the contents of each section.

Finally, a part consists of a sequence of segments. The segments are executed in the order defined by a segment manifest, which allows for the simultaneous execution of more than one segment. This concept is illustrated in Figure 5.3, where each manifest consists of four unique segments. In manifest A, each segment is printed in the numbered order. In manifest B, segments 2 and 3 are printed simultaneously (i.e. alternating contours between each segment). Arranging the segments in this way allows for greater flexibility when planning a part, and provides the infrastructure to bring thermal management into the part for proper re-sequencing of the path segments. The simplified thermal modeling will be discussed in Chapter 7.

5.2.1 Generating 3D contours

Due to the lack of non-gravity aligned slicing software, the raw contours (i.e. slices) generated for use in this framework are made using the metrology software GOM Inspect. Solid CAD models are imported into the software, and cross sections of these solids are generated and

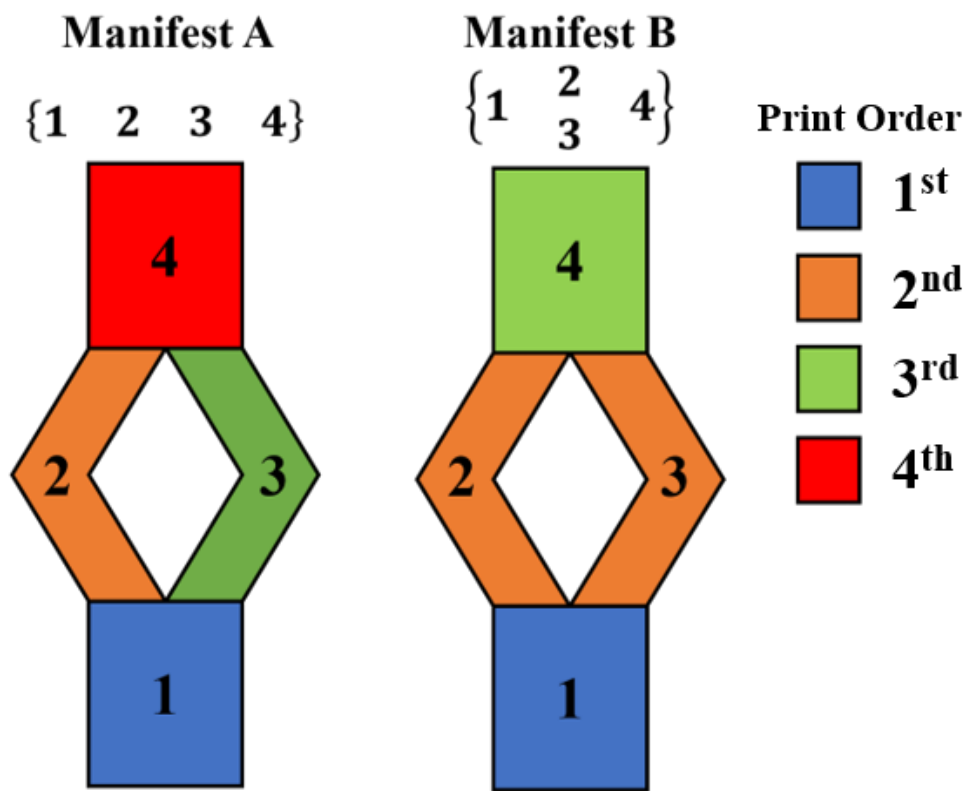


Figure 5.3: Execution of segments According to a segment Manifest

exported as sets of delimited positions along the cross sections. GOM Inspect offers flexible definitions for automatically generating cross sections via various methods, such as along a spline, or radially along an axis. These methods allow for quick, semi-automatic generation of test geometries that cannot typically be created with commercially available slicers. An example of a part sliced using GOM is shown in Figure 5.4. Given that the part was designed with the width of a single bead, the center surface was used as the slice geometry to place the weld beads at the center of the original CAD model. The contours for this geometry are generated along the path curvature, meaning that each layer is spaced the same distance apart, instead of causing a stair step effect on the overhang and curvilinear sections. Geometry does not have to be generated in GOM Inspect, as slices generated in other commercial slicers or other software contain similar global position location and can be organized in a similar fashion for importing into the MATLAB path planning software.

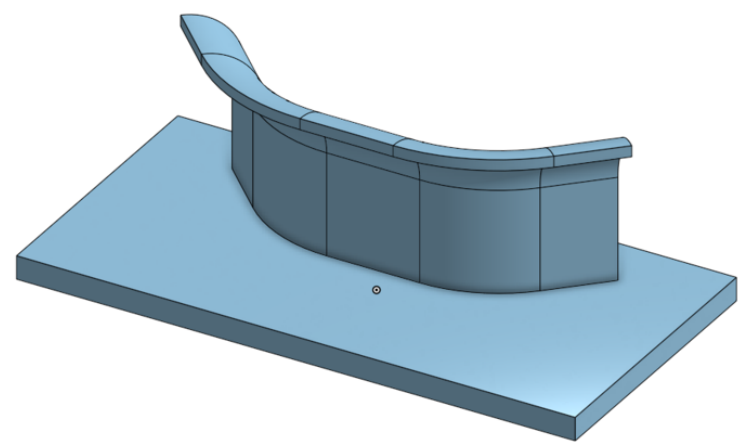
5.2.2 NGA Printing using WAAM

From the previous results in Chapter 4, it is known that severe overhangs can be achieved using WAAM by rotating the weld torch to point in the direction of the overhang. Calculation of the overhang direction, and resultant tool frame, may be computed by comparing the geometry of two sequential contours. Within the present framework, tool frame data is stored within waypoints as a rotation matrix R with respect to the part coordinate frame, as given by (5.1), where z' is the tool vector, and x' and y' are vectors selected to yield a right-handed reference frame. The position and rotation data at each waypoint are combined into a homogeneous transformation matrix, defined in (5.2), where H is the transformation matrix and P is the position $\begin{bmatrix} x & y & z \end{bmatrix}$ of the waypoint relative to the part coordinate frame.

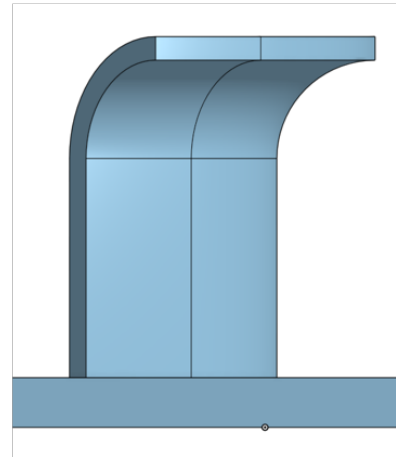
$$R = \begin{bmatrix} x' & y' & z' \end{bmatrix} \quad (5.1)$$

$$H = \begin{bmatrix} R & P' \\ 0 & 1 \end{bmatrix} \quad (5.2)$$

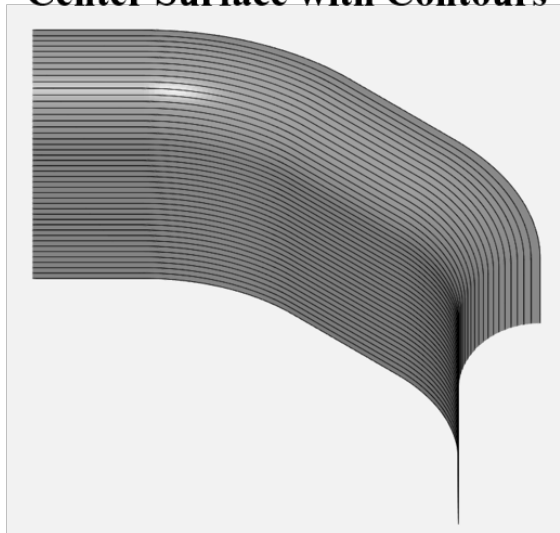
Original CAD



Side View



Center Surface with Contours



Side View Contours

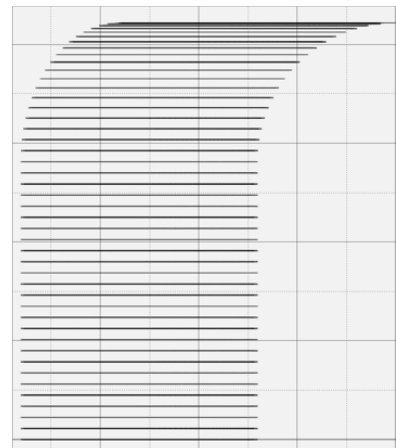


Figure 5.4: Extended Quarter Bowl part Sliced in GOM Inspect

To calculate the overhang direction, and thus the torch angle, the geometry of a contour and the one previous are considered, following the steps shown in Figure 5.5. In a contour, the torch angles are defined for each move. First, the torch angle vector is defined on the midpoint of the current and previous contour. Then, the normal vector between the contours at that point is calculated using vector projection, as described by Equation 5.3, where z is the torch axis (or the Z axis of the tool reference frame), m is the vector between the midpoints of the two Moves, and T is the travel vector along the identified move in the previous contour. Once the vector z is established, the x and y vectors of the frame are determined by travel direction and then the right hand rule. The definition of the x and y vectors of the frame can also be subject to algorithms defined by kinematic relationships or simplifications for complex 3D trajectories.

$$z = m - \text{proj}_T m \quad (5.3)$$

This logic can also be used to automatically categorize segments. If the z vector between two moves is $[0 \ 0 \ 1]$, then those moves are GA. A segment whose moves are all GA can be categorized as a GA segment; a segment whose moves are all NGA can be categorized as an NGA segment; and a segment with a mix of GA and NGA moves may be categorized as a transition between GA and NGA. Since these definitions are also mathematical, they can be used to assign and modify the path plans.

5.2.3 Adjusted Torch Angle and Position

While the orientation of the tool using previous contours is an acceptable initial assumption for assigning trajectories, this is not always the best approach. For particular systems and/or material compositions it may be desired to have a non-perpendicular torch orientation to the previous layer. Additionally, there may be situations where the torch may interfere with already printed features, as illustrated in Figure 2.4. Therefore, low level control of specific waypoints is necessary. The low level control is accomplished by a transformation H_{shift} defined as (5.4), where ΔR is the rotation shift and ΔP is a position shift $\begin{bmatrix} \Delta x & \Delta y & \Delta z \end{bmatrix}$. The new waypoint data may be computed by post-multiplying H by H_{shift} , given by (5.5).

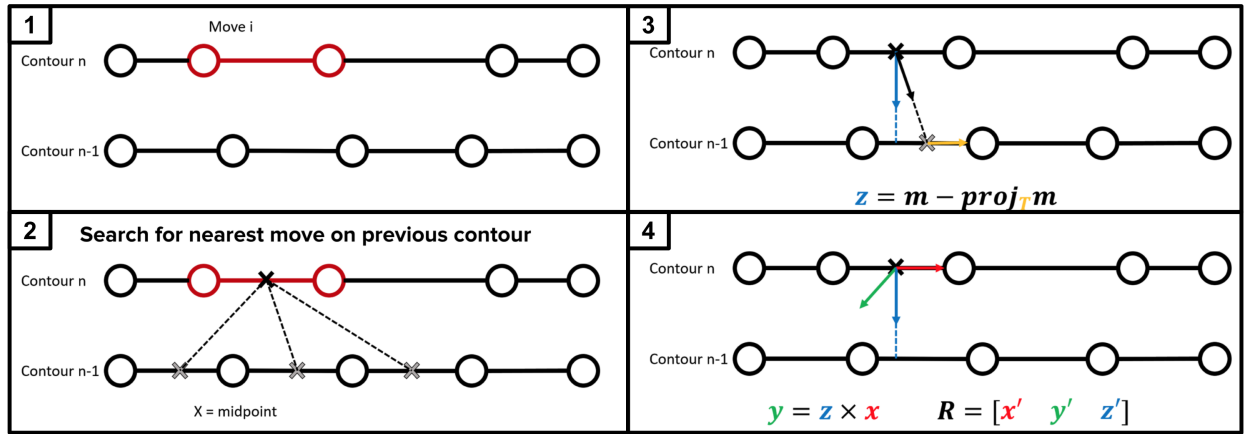


Figure 5.5: Calculation of Overhang Angles and Tool Reference Frame

$$H_{shift} = \begin{bmatrix} \Delta R & \Delta P' \\ 0 & 1 \end{bmatrix} \quad (5.4)$$

$$H_{adjusted} = HH_{shift} \quad (5.5)$$

Using this general approach, any rotation and translation may be easily applied to a waypoint. For most overhangs, it is useful to define x as the travel vector. Under this definition, ΔR may be selected as the elementary rotation about x , as given in (5.6), where θ is the rotation angle. However, for more complex geometry, this simplification may not be appropriate. If a more complex mathematical relationship is desired to define the contours, the path planning software allows easy adjustment to the program to define a new mathematical relationship from the contours. The ease of adjustment for applying relationships will prove useful in Chapter 6 when heuristic experiments are used to define the ideal NGA angle and shift for a range of overhang values.

$$\Delta R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \quad (5.6)$$

5.2.4 Constraining Tool Frame Rotation

The MIG welding process requires 5 degrees of freedom (DOF) to locate and orient the welding torch in space because the rotation about the torch approach vector is inconsequential. Therefore, it is necessary to apply extra requirements to constrain the x and y tool frame vectors. A simple, intuitive method to describe R is by defining x as the travel direction at each waypoint, and then defining y as the cross product of z and x . This fixes the tool orientation with respect to the path. While this approach may be useful for applications that require a fixed orientation along the path (such as closed loop control based on image processing), it often does not yield favorable robot trajectories due to manipulator kinematics or part placement relative to the manipulator base. Another

approach is to fix the plane in which either x or y must sit. This provides trajectories which may be more easily achieved by a manipulator, but this solution degenerates when the tool vector is perpendicular to the fixed plane. Examples of these approaches are shown in Figure 5.6. While out of the scope of this research, manipulator kinematics must be considered for future work if NGA methods want to be applied for increasingly complex trajectories.

5.3 Trajectory Planning Application

This framework has been implemented with a GUI, as shown in Figure 5.7. The input to this GUI is sequences of XYZ points (such as cross sections generated in GOM Inspect) that represent the positions along the tool path. These sequences are turned into contours within a part. From here, a user may choose from a host of post-processing algorithms, such as updating the rotation of the tool frames at each point or setting the minimum move length. After setting up the trajectories, a .path CNC file may be exported for use in an offline robot programming application such as Octopuz, which is the 3rd party kinematic simulation and Kuka Robotics Language (KRL) posting software used to execute these trajectories.

5.3.1 Quarter Bowl Geometry Path Planning

The framework has been implemented at the University of Tennessee and provides an avenue for planning and executing complicated geometries. The software framework was built with the intention of defining torch heuristics for NGA segments to ensure that near net shape of features can be achieved. To show the effectiveness of the planning, consider the "Extended Quarter Bowl" Geometry as seen in Figure 5.4. This geometry is challenging due to the NGA segments that are also curvilinear. The part contains 2 main segments, the GA wall and the NGA overhang section.

This geometry would have been particularly tough to plan with the previous methods. Each new tool frame for each waypoint would have needed to be identified and assigned by hand. With the application of the path planning software, only a few simple algorithms were applied to these contours after they were imported into the application. In all, the planning after given contours for the entire part takes less than an hour.

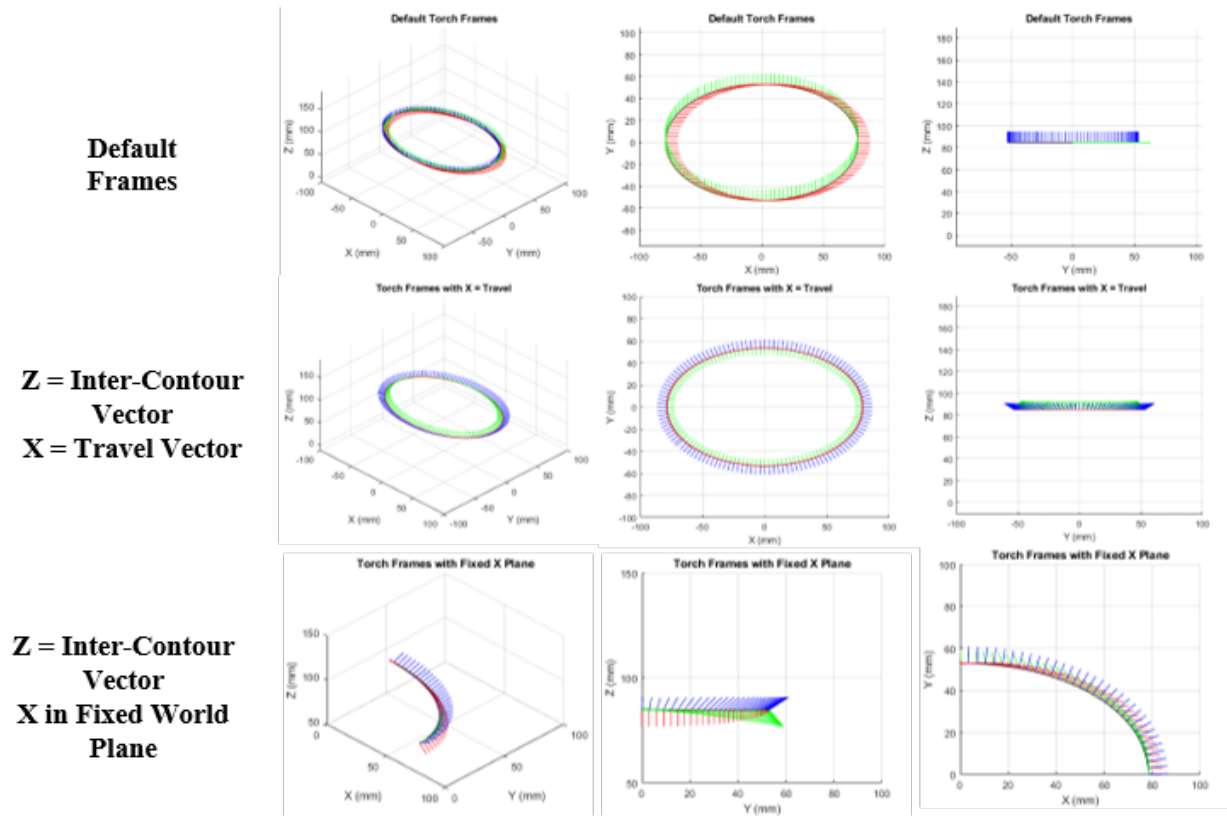


Figure 5.6: Example Tool Frames for NGA Section of an Elliptical Bowl

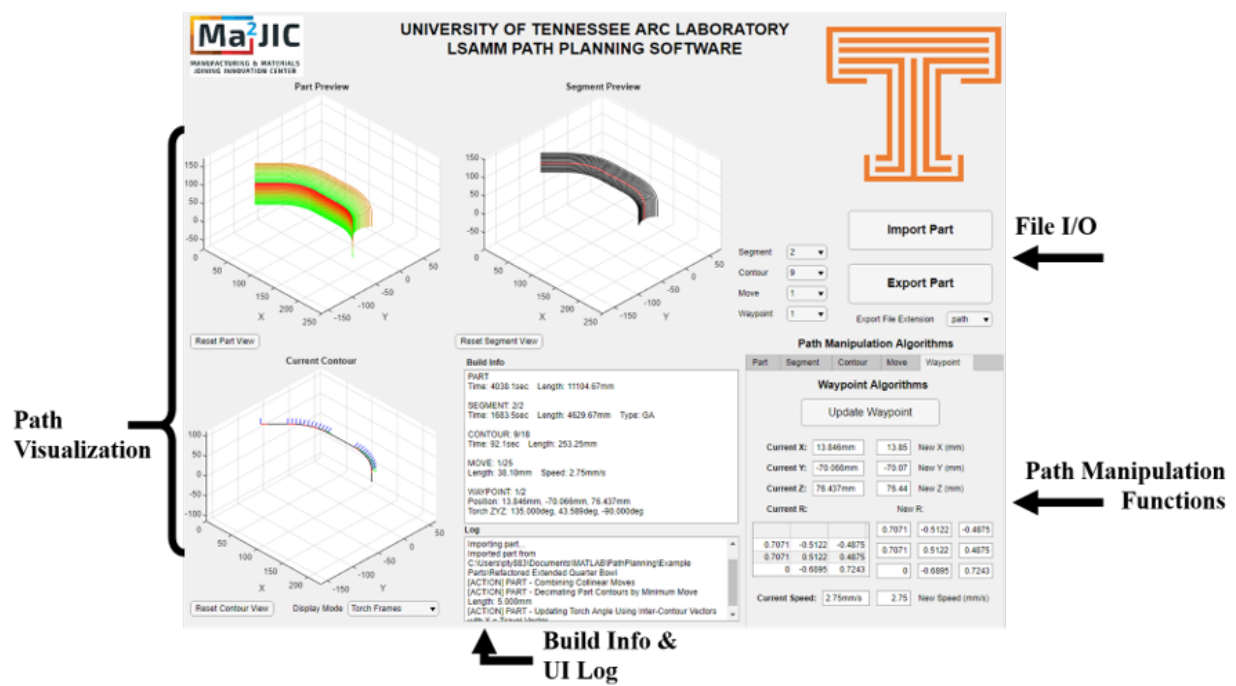


Figure 5.7: UTK Path Planning Application



Figure 5.8: Views of the as built extended quarter bowl geometry produced using the new path planner software and methodology. The entire part planning takes less than a few hours including contour generation, path planning automatic NGA orientation calculations, and welding parameter assignments with KRL generation in Ocotopuz.

The final build of the extended quarter bowl was 45 layers and took about 1.5 hours to complete. The part had 30 second waits between each layer. The demonstration part completed every layer¹. The part can be seen in Figure 5.8 from a front(left), top(middle), and back(right) view. The only initial issues for the quarter bowl stemmed from the kinematics of the deposition robot. The part had to be turned sideways to ensure that the robot would not hit a singularity point during layer deposition or exceed the axes limits. Given that the path planning software does not account for robot kinematics, this is to be expected. However, tackling the kinematics problem still remains outside of the scope of this work.

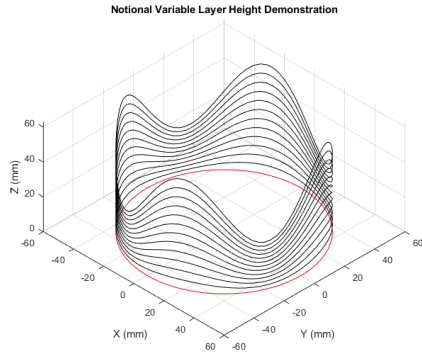
5.4 Implications for Trajectory Planning of NGA Segments

The focus of this research has been on how NGA methods can be used to improve the near net shape of parts with complex geometries, specifically large overhangs, without introducing process changes. As mentioned throughout the chapter, the customization of software makes it very easy to build new functions based on the information hierarchy and to apply changes to the trajectory planning using algorithms. Low level control of torch position and orientation is necessary, but also giving those specific data points context within the information hierarchy of the path planning data structure allows custom algorithms for planning that are not typically seen in commercial slicing or path planning software. Slicing and bead model(s) were excluded from the path planner as at the time of development the extent of the effectiveness of NGA segments were unknown. The first goal of this software is to take any generated contour and have high level and low level changes be applied quickly and robustly for experimental results. An example of the code for the path planner can be found in Appendix D by downloading the code from the lab GitHub for use on general AM applications.

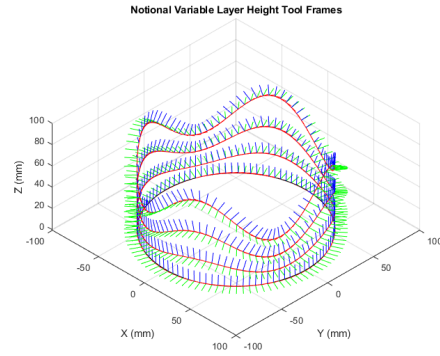
To demonstrate the robust capabilities of the path planning software, contours representing a variable height slice cylindrical shape were generated in MATLAB. The contours

¹For a video of the full build: <https://youtu.be/H5qBMZo6k0s>

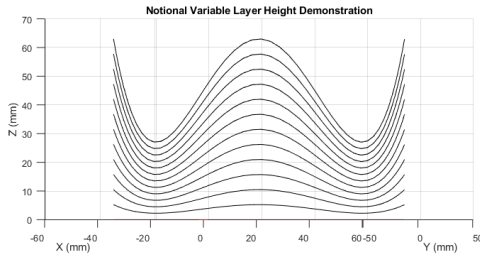
were generated from a function, and have variable height and orientation for every layer. Example of the segments and their trajectories generated with the path planner can be seen in Figure 5.9. The trajectories generated rely on the previous algorithms outlined in Figure 5.5, and the algorithms run within seconds after the layers are imported into the path planning software. The path planning software can generate and execute these trajectories, but it relies on a previous understanding on the modulating of the process parameters to produce these height changes. The stage is set for when an intricate understanding of bead geometry to process settings can be ensured, the path planning software can handle any complex trajectories that are necessary to complete the part in a smart and effective fashion for additive manufacturing processes.



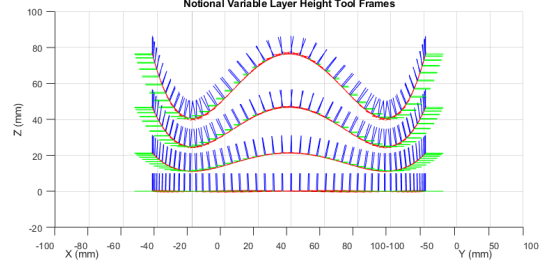
(a) Iso view Layers



(b) Iso view Trajectories



(c) Side view Layers



(d) Side view Layers

Figure 5.9: Generated variable height contours and the resulting trajectories generated from the path planning software developed at the University of Tennessee. The trajectories were automatically generated by applying Equation (5.3) simplification for perpendicular torch angles from the previous layer.

Chapter 6

Heuristic Torch Behavior of NGA Segments

Given the improvements outlined in Chapter 5 to the UTK path planner capabilities, research needed to hone in on the specific question raised from Chapter 4: How can we identify the ideal torch rotation and position associated with a process setting and overhang type? Determining these ideal torch angles and shift for the system can be used to provide a pathway for understanding to what extent design of a geometry can incorporate overhangs.

6.1 Experiment Design and Quantitative Methods

To help understand the fundamental effects of the torch rotation and position shift, researchers designed a system of experiments and analysis to help identify correction values to the torch angle. The goal of the experimental design was to apply the ideal torch rotations and position shifts to the half cylinder geometry. If the fundamental physical effects of the wall growth and weld bead deposition could be identified and corrected with open loop techniques, the near net shape of the new half cylinder geometry with the "ideal" torch angle and shift should show significant improvement from the previous near net shape outlined in Chapter 4. Identifying and applying the ideal torch angles should shed insight into the fundamental understanding of how, and to what extent, that these open loop torch planning

methods can be used to help reach near net shape. Identifying these fundamental torch heuristics can then point towards future works for specific systems or analysis tools.

6.1.1 Analysis of Near Net Shape

The first step is identifying a quantitative measurement to analyze near net shape for a growing overhang section. For this application, the focus was on the growth direction of the layers perpendicular to the base plate. If the overall growth direction and displacement can be predicted and quantified, experimental results can drive the choice of corrected orientation and position shift. As with the work seen in Chapter 4, the scanned as built geometries were registered and compared to the idealized CAD geometry produced from the path plan of expected 2.25mm layer height and 6mm layer width. Comparing the idealized CAD and contours to the as-printed scanned geometry, quantitative measurements were identified for each type of section. The overall workflow is outlined in Figure 6.1. There are three main sections for this workflow, identified in the three pictures. First, a test matrix geometry with varying torch angles and/or shifts will be aligned to the expected CAD. These aligned geometries can have cross sections of each as-built wall extracted and analyzed for steady state and transient growth. All of this analysis is completed using a combination of GOM Inspect and MATLAB.

The test matrix CAD is represented as nine thin walls growing perpendicular to the base plate. The walls are all expected to grow perpendicular to the base plate, regardless of the varying torch angles, shifts, or base angles that the test matrix CAD is mounted. Given the improvements to the path planner outlined in Chapter 5, we can assign each of the thin wall contours with varying path plan changes like updating torch angles for each contour or shifting an entire wall contour across the base plate. This means that while the CAD contours grow perpendicular to the base plate, the associated contour property is modified for each wall. After using the path planner to modify the test matrix build for certain properties, the builds can be executed and then scanned using the Arctec Spyder outlined in Chapter 4. After scanning, the scan is imported into GOM Inspect and aligned with the base plate of the desired CAD geometry. Then, the wall near net shape can be analyzed given the deviation and as-printed results of the build. The analysis needs to focus on how

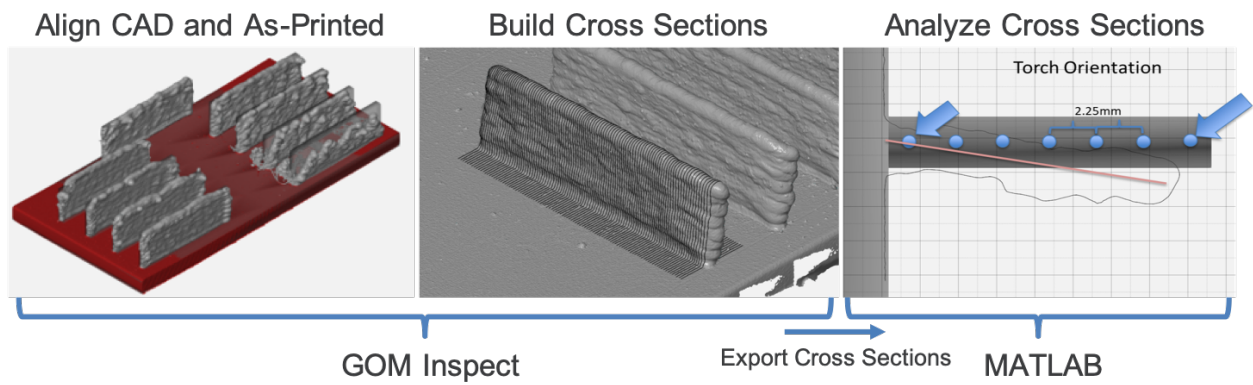


Figure 6.1: Generalized figure showing the methods for analyzing a wall growth for near net shape analysis. The alignment of the CAD and as-printed geometry to generate cross sections of the wall are done in GOM Inspect. The final quantitative analysis is done in MATLAB using exported cross sections. The analysis can be compared to the ideal planning sections.

effective a certain path plan change is to help build the wall to a better near net shape, so particular focus is given to how effective the path planning changes can reach the near net shape.

Generalizing the growth of the walls based on a linear representation can be used to provide a quantitative method for analysis of these NGA methods. For a given overhang, it may be seen that the steady state accumulation effects are different than the transient displacement effects of bead accumulation, like the effects seen in Chapter 3. By taking a linear approximation of the top and bottom surface of the wall (calculated by MATLAB *fitlm* command), a center line for each cross section can be identified by the average of the top and bottom surface linear representation. m will be defined as the slope of the line as seen in Equation (6.1). The slope indicates the steady state growth of the wall relative to the top and bottom surface. A straight wall would have a degree value (m value) of 0, indicating that the wall is growing perpendicular to the base plate.

$$m = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1} \quad (6.1)$$

The b value, or the slope intercept, is indicative of the transient effect of the bead displacement relative to the growth vector. The slope intercept can be used to indicate how far the thin wall base is displaced from the desired location. Given that the gravity effects are evident as soon as the deposition begins, the slope intercept will directly correlate to a position shift along the deposition path. Given that previous work with the full cylinder shows that less than desirable torch orientations can be improved by shifting the bead along the path, it is reasonable to think that there is a combination of best case orientation and angle for a given overhang angle. The linear slope theory approximation provides a simple and quantitative measurement that can be used to evaluate the effectiveness of the NGA techniques on helping improve overhang near net shape. The full equation is given in Equation (6.2). A figure outlining a single cross section and resulting center line and analysis of these approximations can be seen in Figure 6.2.

$$y = [\text{Steady State Wall Growth}]x + [\text{TransientWallDisplacement}] = mx + b \quad (6.2)$$

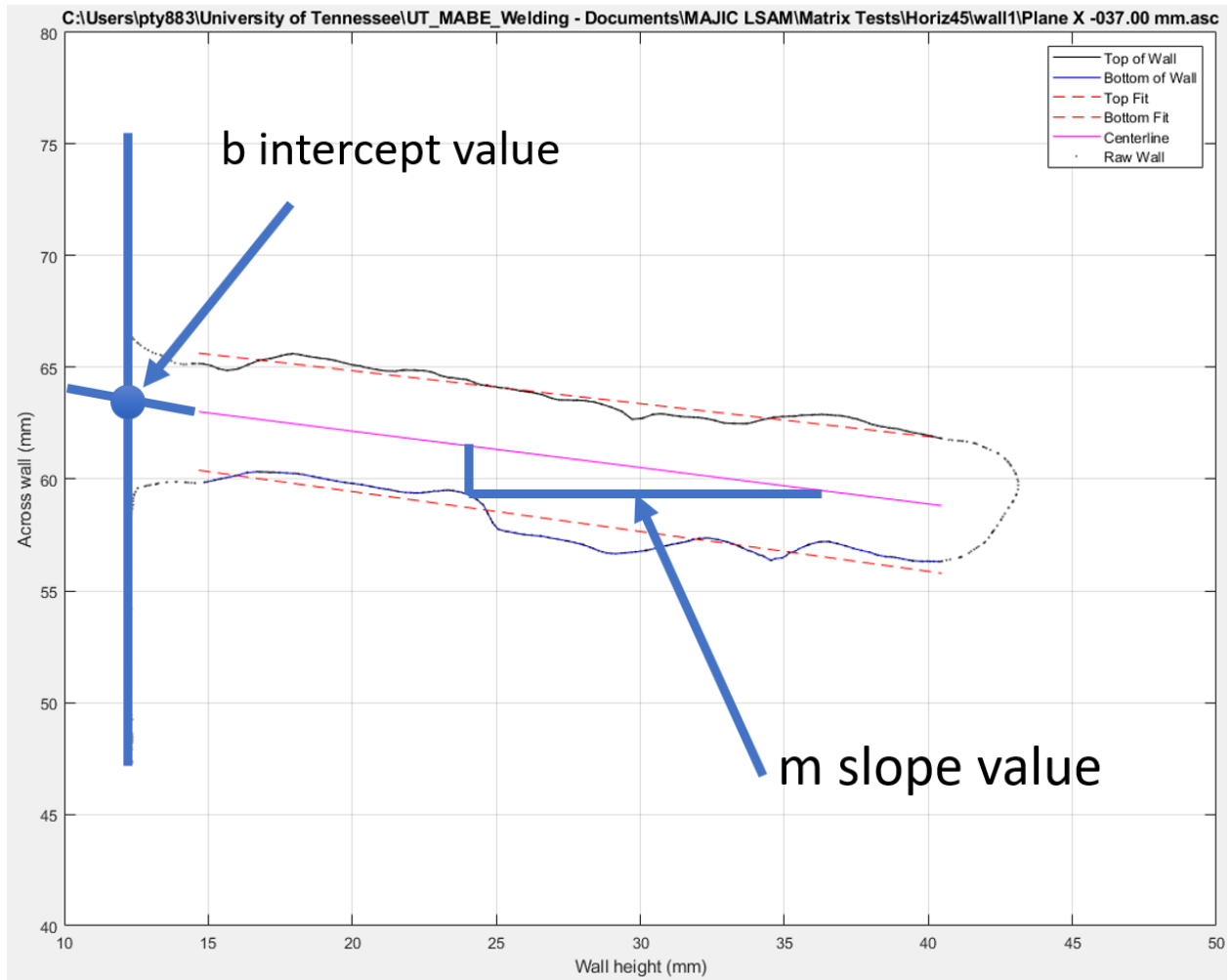


Figure 6.2: Picture from MATLAB software of a chosen cross section used for analysis of the wall. The m and b values are shown and labeled, but found using MATLAB analysis tools and programs.

MATLAB scripts were generated to help streamline this analysis after scanning the as-printed geometries after creating their path plans and depositing them. After aligning to the base plate, the as-printed geometries have an expected location in the coordinate space of the base plate which can be used to identify evenly spaced 1mm cross sections for each wall. All of the linear fits of the top and bottom surface were compiled in MATLAB to determine the center line of the wall growth and the resulting slope and intercept associated with each cross section. These single cross section results can be extracted separately or averaged for analysis purposes. The slope analysis MATLAB function can be seen in Appendix D.

6.1.2 Experimental Design

The experimental design is generalized in Figure 6.3. Each of the test matrix geometries has 9 walls with varying torch angles from -40° to $+40^\circ$ relative to the base angle in 10° increments. The 40° maximum torch angle is the largest angle that could be reached without the torch clipping the base plate. With no waits between the walls, a matrix test with 9 walls of 15 layers tall takes approximately 3 hours. To complete the analysis takes another 2-3 hours of scanning, file conversion, and then analysis in the MATLAB software. Given that the welding, scanning, and analysis of these plates is time intensive, a smaller spectrum of base angles were chosen (0° , 10° , 25° , 45° , 65° , 90°). Although fewer base angles were chosen, these angles will still represent the full spectrum of overhang values associated with the half cylinder geometry, and successful analysis and application of the ideal torch angle and shift corrections should show an improvement to the near net shape of the as-built geometry.

An example of these parts being welded can be seen in the footnote below¹. It is again to be emphasized that these test matrix geometries were completed entirely open loop, with no corrective action taken during the tests. The geometries were pre-planned using the UTK path planner software and then executed with stops only to clean the previous layers if there was an arc start error due to silicates on the top surface. A total of 9 test matrix tests were completed: one for each base angle and then a position shifted version of the 45° , 65° , and 90° matrix base angles. A summary of all of the builds can be found in Appendix B.

¹For a video of a 65° and 90° experiment: <https://youtu.be/x22TFT94fUc>

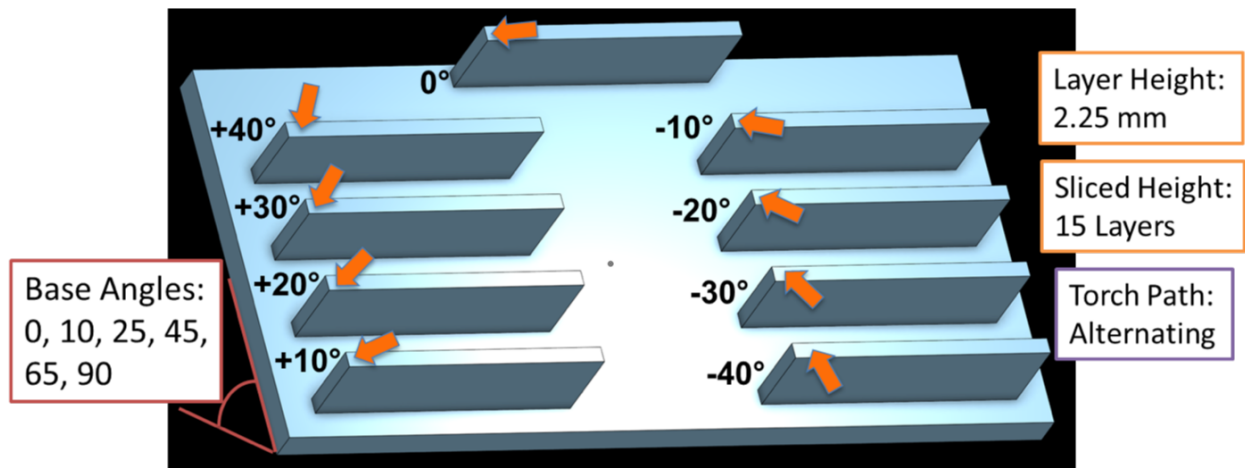


Figure 6.3: Matrix Test design with the CAD design. Each wall was 15 layers tall and each plate had 9 single bead walls with variable base plate angles and torch angles.

6.2 Experimental Results

6.2.1 Initial Geometry Analysis and Observations

Three matrix tests with base angles of 45° , 65° , and 90° were executed on the system. The expected CAD was built using the previous physical relationships - meaning that the walls were assumed to grow perpendicular to the base plate, with only the torch angles changing for each thin wall on the base plate. An example of an as-printed matrix test after it has been aligned in GOM Inspect can be seen in Figure 6.4.

The analysis of the matrix tests can be seen in Appendix B. Both analysis of the b and m results can be seen for each wall for every matrix test experiment. For each wall, the average intercept and slope can be extracted for all 100 cross sections and used for an aggregated analysis. The initial values for the aggregated slope and deviation angles for the three tests can be seen in Figure 6.5. Blue is 45° base plate orientation, yellow is 65° base plate orientation, and red is 90° base plate orientation.

The first trend is the behavior of the slope of all three initial tests. Figure 6.5(a) shows that the wall slope has an almost identical behavior for each of the base angles. All of the experiments aggregated slopes have a roughly 3rd order behavior on what torch angle relative to the base plate produced an ideal wall. This quantitative observation can be confirmed qualitatively by observing the underside of the walls from the aligned CAD like Figure 6.4. For the more negative torch angles relative to the base plate the build are under-built (blue) versus for more positive torch angles relative to the base plate having over-built (yellow/red). These are reflected in the slope calculations by showing that the average build slope reflects this directionality that the torch angle imparts on the near net shape.

The intercept deviation in Figure 6.5(b) has some unexpected results with the 90° wall having some of the smallest deviation at the edges while the 45° and 65° wall having the worst deviations. By going back and observing the physical walls associated with the 90° base plate, some of this can be attributed to the wall build quality. For the large negative torch angles (-40° and -30°), the wall contained major undulations on the final surface, which means less data to determine the top and bottom linear representation of the surface. However, the $+40^\circ$ and $+30^\circ$ torch angle final geometries are acceptable for quantitative analysis.

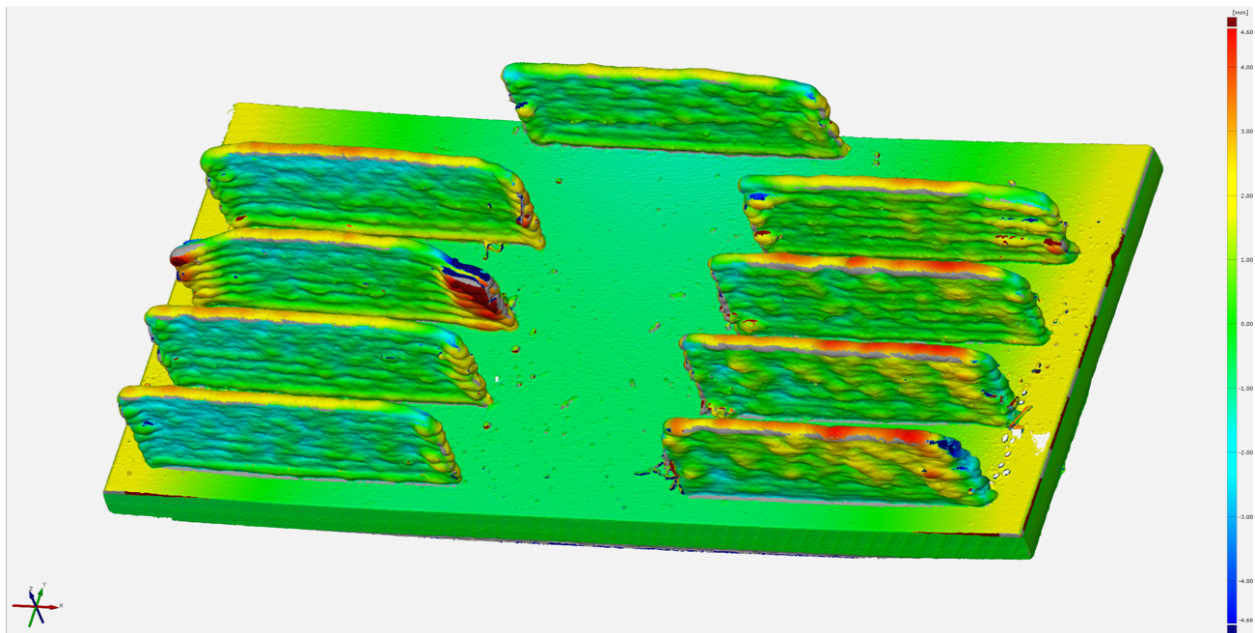
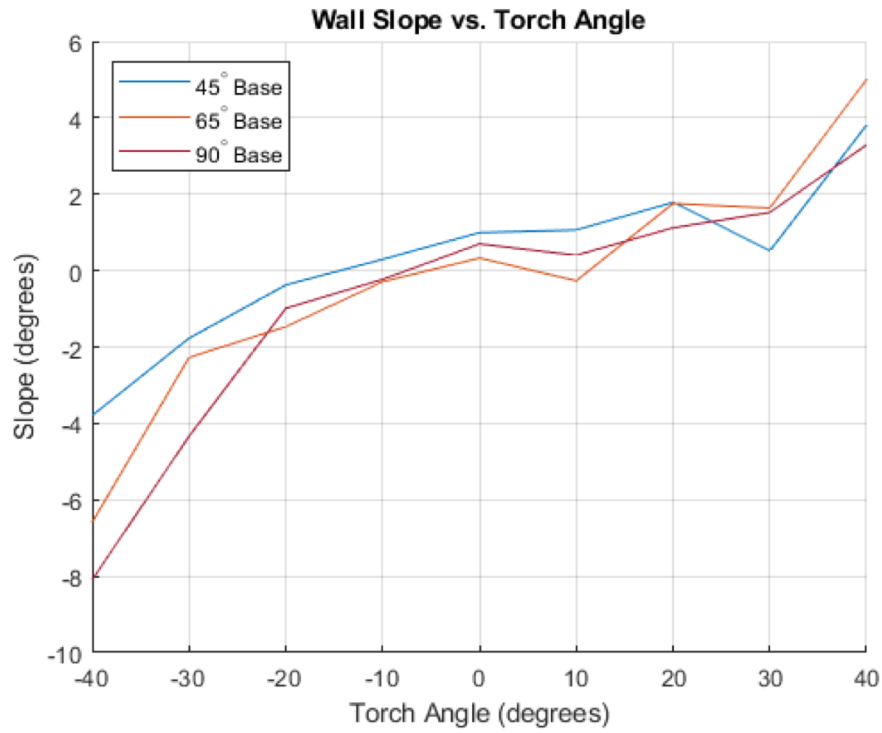
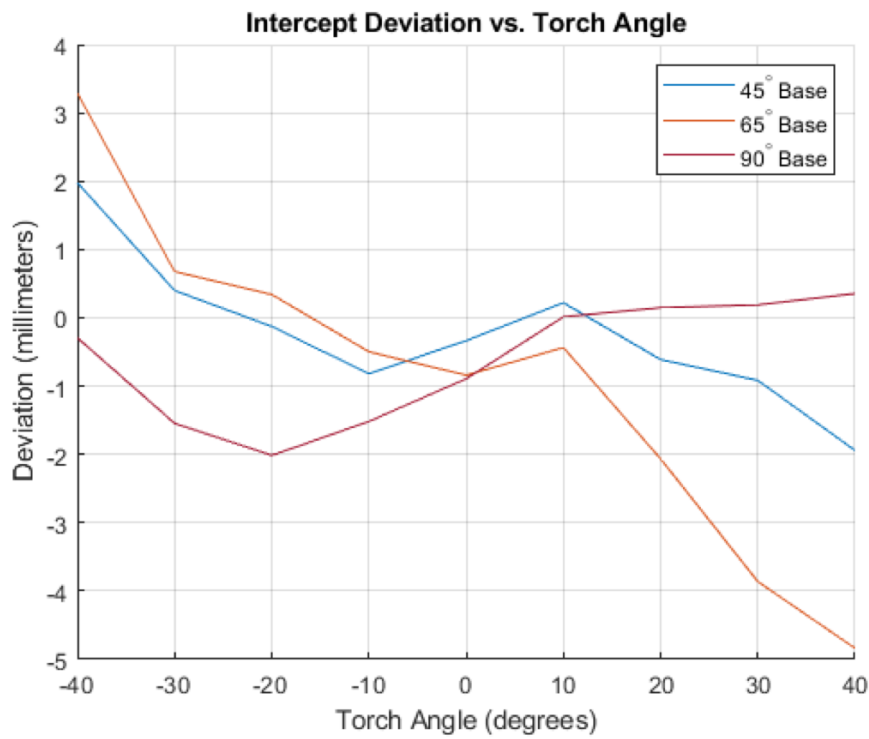


Figure 6.4: Matrix Test aligned with the expected CAD in GOM. The relative relationship to the expected walls can be seen with red representing overbuild and blue representing under build.



(a) Slope vs. Torch Angle



(b) Deviation vs. Torch Angle

Figure 6.5: The results of the aggregated slope and deviation values for the original 45, 65, and 90 base plate with respect to the torch angle.

So from the framework setup for analysis, both observable and non-observable effects of the torch changes for as-deposited geometry can be quantified. The analysis can be used to update our understanding of how modulating torch position and shift can be used to influence growth direction and therefore better near net shape for varying levels of overhang.

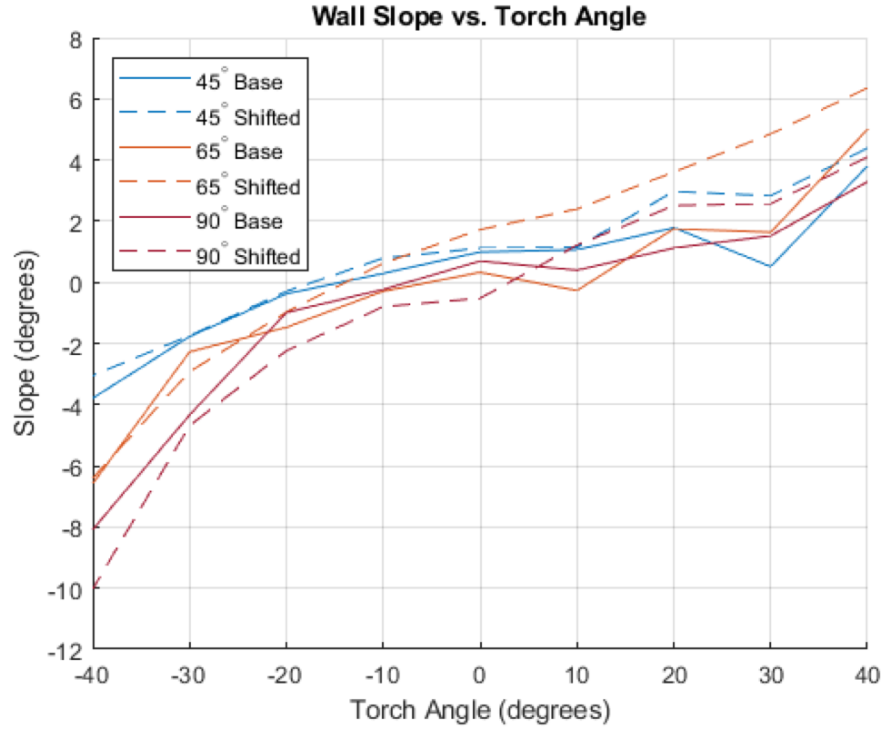
6.2.2 Wall Intercept Correction Effectiveness

Now that a baseline for the slope and intercept was established, the test matrix was repeated with simple changes to the path plan to help determine the effectiveness of the NGA methods. The first step was honing in on the intercept values since those seem to have such different behaviors (as seen in Figure 6.5(b)). From the original builds, the average intercept deviation was determined, and then that value applied to shift the entire wall contours up or down on the base plate. The goal was to shift the overall deviation closer to 0 even for the more extreme torch angles and base shifts. A table of the shift values can be seen in Table 6.1, which is taken directly from the average deviation for each set of base plate and torch angles. Each of the wall's 15 contours were shifted in the direction down (negative) or up (positive) the base plate based on the quantified average intercept. After applying the shifts with the same torch angle values, the three test matrix examples were executed and analyzed. The comparison results of the control base plates to their new shifted walls can be seen in Figure 6.6.

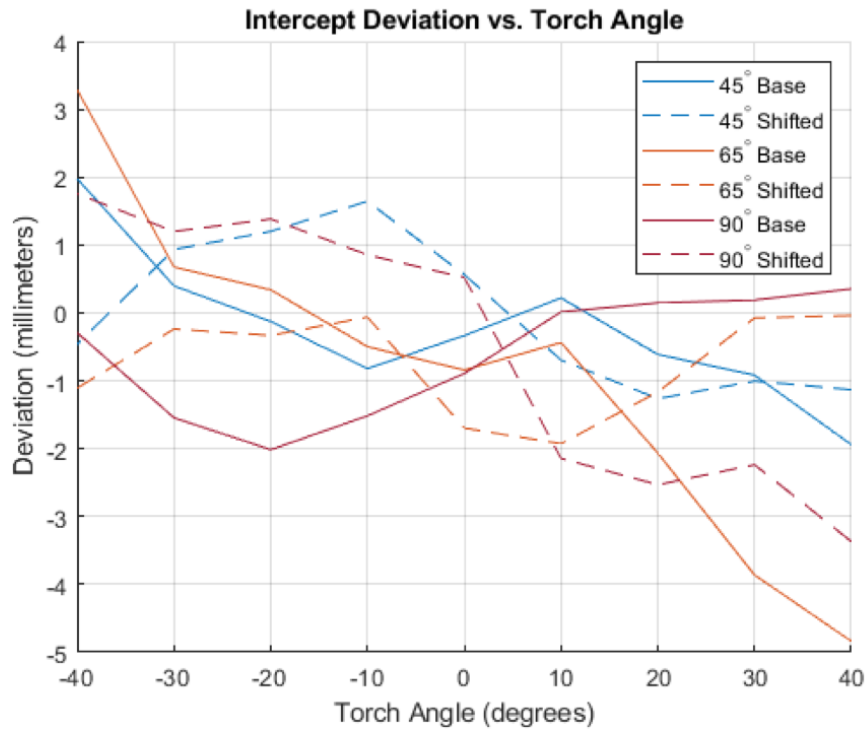
While the deviation shift for the extreme torch angles generally improved the results for the 45° and 65° walls, the 90° base plate walls were significantly worse than the first attempt. With a compensated intercept shift for each wall, the 45° and 65° walls definitely improved in their slope intercept location for the more extreme torch angles for both sides. However, their less severe torch angles actually were further deviated from their ideal intercept value. The inconsistent results on the deviation changes point to outside process inconsistencies which cannot be accounted for with just a simple position shift. This point is only emphasized when looking at the slopes of the new walls in Figure 6.6(a). Generally the behavior of the walls are fairly similar, but specifically for the 65° wall, there is more than 2° difference on the slope change. The only change is the physical location of the contours on the plate, which should not effect the slope calculations if the process was perfectly consistent. In fact,

Table 6.1: Shift values in millimeters from Control Tests

Base	-40	-30	-20	-10	0	10	20	30	40
45°	-1.978	-0.4002	0.1263	0.8196	0.3329	-0.221	0.6110	0.9158	1.941
65°	-3.289	-0.6770	-0.3417	0.4972	0.8402	0.4356	2.0646	3.861	4.837
90°	0.2923	1.543	2.014	1.516	0.8907	-0.0152	-0.1488	-0.1903	-0.3549



(a) Slope vs. Torch Angle



(b) Deviation vs. Torch Angle

Figure 6.6: The results of the aggregated slope and deviation values for the original 45°, 65°, and 90° base plate with respect to the torch angle plotted as solid lines and the new walls with different deviations applied.

given that the walls were deposited and analyzed in the same manner, the issues pervading this analysis seem to point to outside process effects which are not accounted for in the sub millimeter level necessary for this analysis. For the time being, it was decided to ignore the deviation of the intercept given that a simple correction seemed to be completely ineffective for improving the original wall builds, but implications on why this occurred will be discussed at the end of this chapter.

6.2.3 Ideal Torch Angles for Overhangs

While the effects of the intercept deviation cannot be accounted for using a torch position shift, there still remains a chance that the slope deviation can be used to help dictate an ideal torch angle relative to the overhang angle. Since the wall slopes contained the same behavior for both runs of these walls, it is reasonable to believe that the steady state growth can be accounted for in the planning stage. So, using the same experimental setup, researchers decided to print 3 more walls to help understand the behavior of the steady state growth with respect to base plate angle and torch orientation. New experiments with the base plate at 0° , 10° , and 25° were completed to help identify the appropriate behavior. These walls and their resulting geometry and slopes can be seen in [Appendix B](#).

Given the previous struggles with analysis of the torch intercept deviation, it was determined that a few changes need to be made to the analysis for the ideal torch angle. Therefore, the analysis was refined in the following ways:

- Edge effects need to be ignored in the steady state analysis, so the 100 contours are reduced to 80 (roughly equivalent to 10mm from each edge) to ensure that only the center of the walls are used to identify the steady state slope
- The bottom 5 layers are ignored due to the fact that the first 5 layers will have a different accumulation effect since they have not experienced similar thermal cycles and conduction pathways when compared to the later layers
- The torch angles of 40° generally cannot produce full geometry, so they are ignored for this analysis even though they have been printed with each of the test matrices

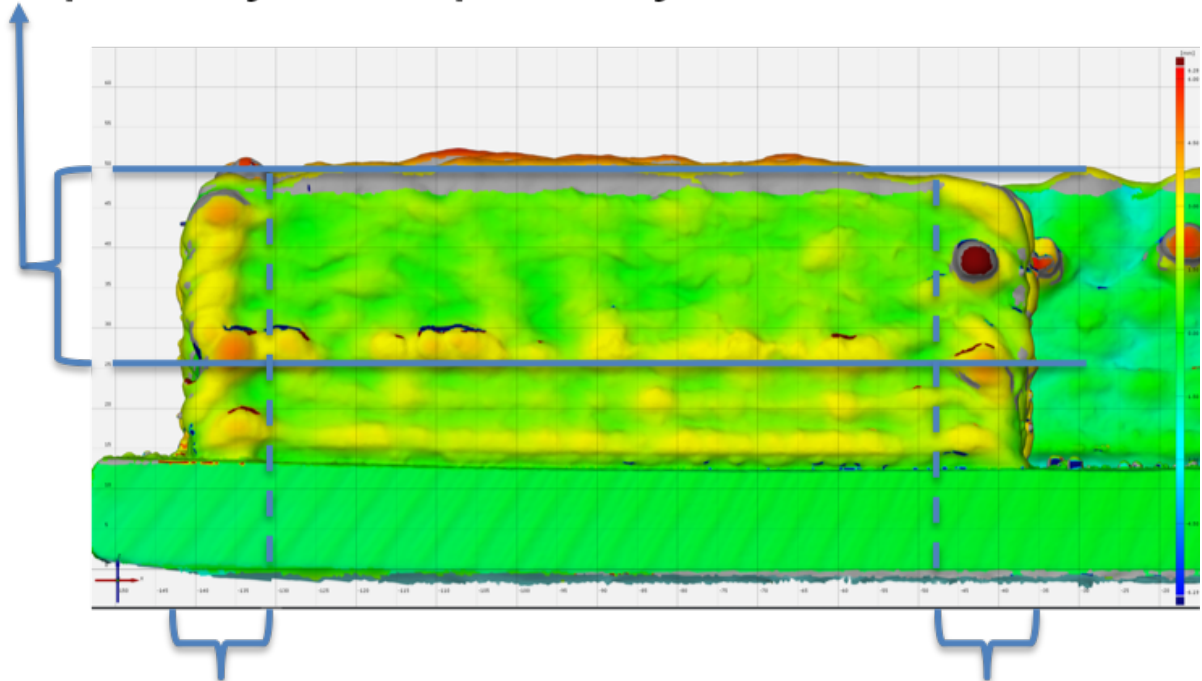
Figure 6.7 shows the physical extent that this more focused analysis is trying to quantify. The changes should help more closely identify the steady state effects by removing some of the areas where the transient effects would be more prevalent. The analyses on the walls were rerun with these changes to help identify the steady state change that occurs with torch angle changes relative to the base plate angle.

6.2.4 Quantifying Ideal Torch Angle

An ideal torch correction offset (referred as the "ideal" torch angle) can be identified from a best fit polynomial identified from a re-analysis of the experimental wall setups. A linear approximation is taken of the 8 points from -30° to $+30^\circ$ torch angle test matrix results at each base angle. The zero crossing should approximate the ideal torch angle relative to the base plate at which the steady state slope of the wall is growing perpendicular to the base plate. The ideal torch angle can then be identified for each of the test matrices and another polynomial generated from the predicted values to apply to the half cylinder geometry. An example of one of these linear graphs and the 1st order approximation can be seen in Figure 6.8.

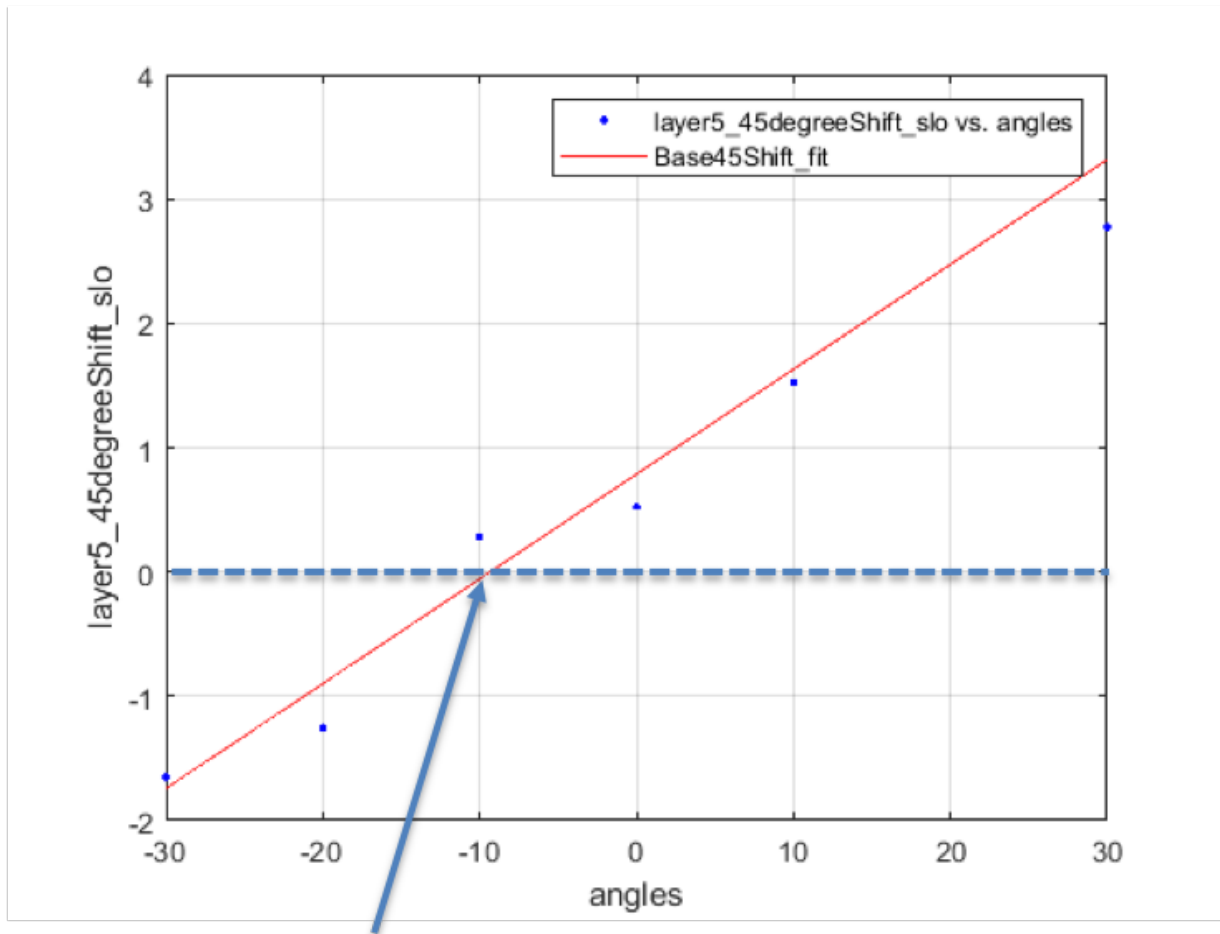
After analyzing all of the separate base plate experiments, a summary of these tests and their fits is shown in Figure 6.9. The linear approximation of these values are all relatively close - and an enlarged graph with their crossings can be seen in Figure 6.10. Figure 6.10 contains the first order fits of all of the wall analyses zoomed in around their crossing to identify the ideal torch angle for the given base plate angle. The values of the zero crossings are summarized in Table 6.2. The crossing values that are used to identify the ideal torch angle do not provide a robust analysis of the full spectrum of overhang angles, but for the purposes of this demonstration required around 100 hours of welding and analysis. It was decided to not identify more points due to the considerable amount of analysis needed to produce the results, and these simplified results should show improvements to the half cylinder geometry even with the smaller amount of reference points. If effective, future works could be used to streamline and expand this analysis to produce a process map of the ideal torch angle to overhang range.

Top 10 layers slope analyzed



Edge Effects from
Start/Stops

Figure 6.7: A GOM Inspect section of a thin wall from the test matrix. The blue lines show the area of the wall that will be used to analyze steady state slope to get the ideal torch angle for overhangs.



Ideal Torch Angle Value

Figure 6.8: A graph from MATLAB that shows the 1st order linear fit with the 45° Shifted base plate angle and where the ideal torch angle is located from the 1st order approximation of the slope behavior.

Table 6.2: Zero Crossing Values for Base Angles

Base Angle	0°	10°	25°	45°	65°	90°
Ideal Torch Offset Angle from Normal	1.149°	-10.16°	-4.933°	-7.312°	-1.079 °	-2.963°

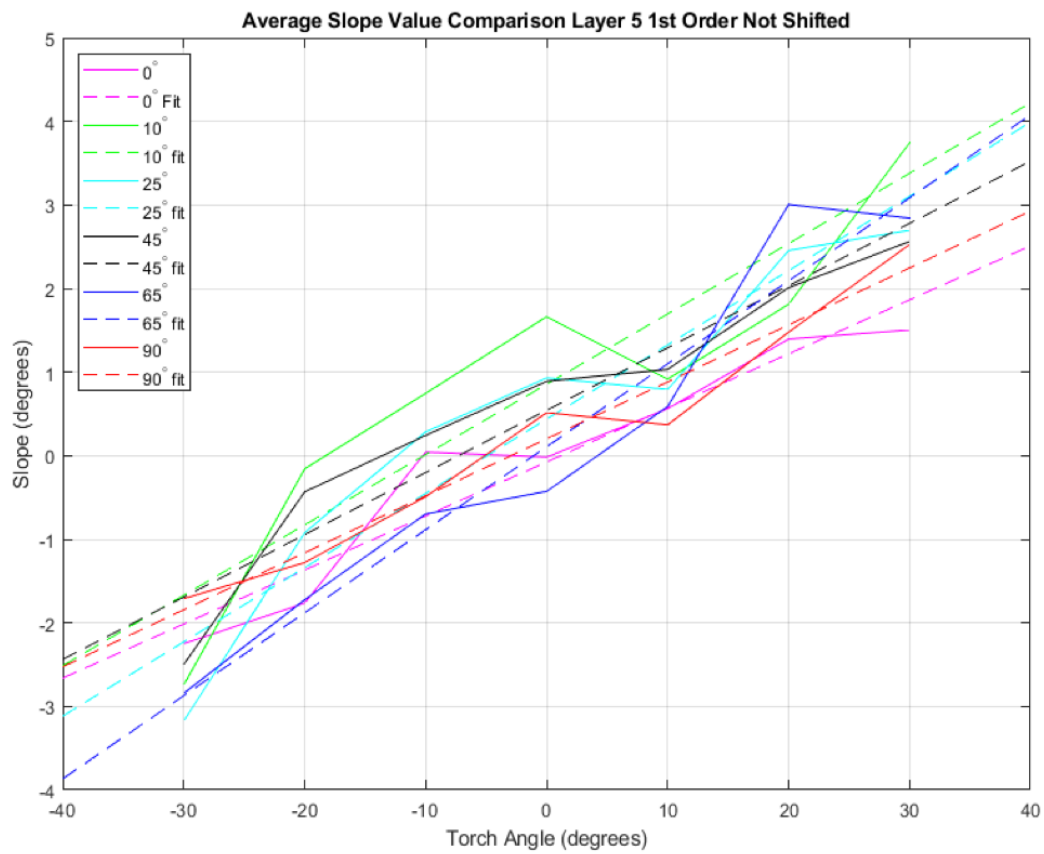


Figure 6.9: A graph from MATLAB that shows the 1st order linear fits for all base plate angles and the original data found through the analysis of the matrix tests.

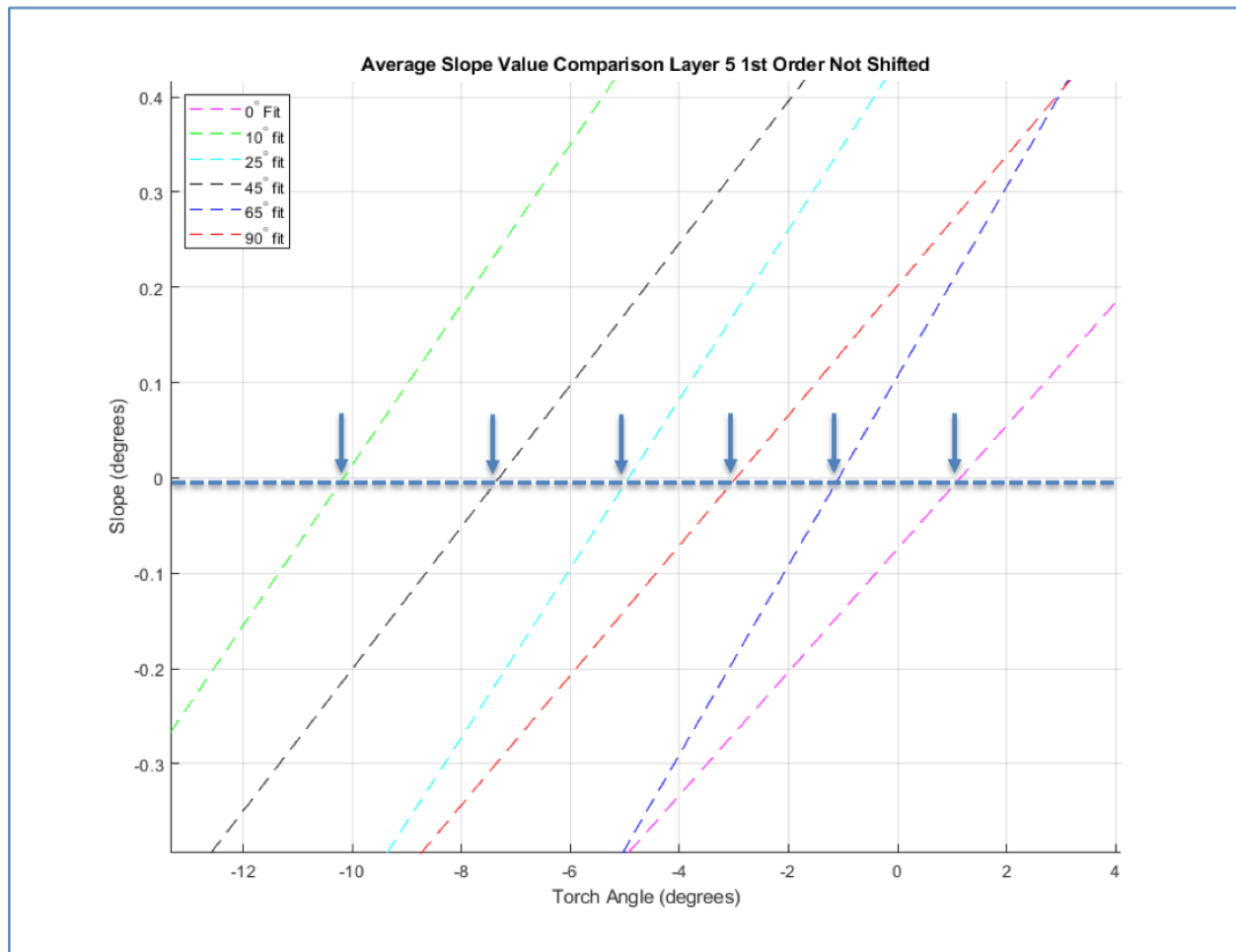


Figure 6.10: A graph from MATLAB that shows the 1st order linear zoomed in on the zero crossing with the arrows pointing out the ideal torch angle for each base plate orientation. These points will be used to identify the ideal torch angles for a part.

6.2.5 Ideal Torch Angle Application

Now that the ideal torch angles have been defined, this information was used to generate a best fit torch angle across the 0° to 90° spectrum. This continuous function can be used to define the ideal torch correction based on the overhang angle. The function that had the closest representation to these data points was a 3rd order fit. The continuous function as defined gives the appropriate correction value with respect to the overhang angle. A figure of the continuous correction function can be seen in Figure 6.11. The polynomial has behavior where the largest correction angle is at around 25° , while the smallest corrections can be seen as the torch approaches the 0° and 90° overhang.

Given the defined continuous function the next step was applying these correction values to demonstration geometry. The half cylinder geometry was defined in Figure 4.1 as a continuously variable overhang geometry. The geometry has a range of overhang values from -90° to 90° . By applying the correction function, there should be improvement to the near net shape of the final deposited part. Chapter 5 outlined the path planning software that can take into account the correction function determined from the experiments. The software can take in the function based on identification of the overhang value and then apply the proper correction to the tool paths generated from the values. The application of these values can be seen in Figure 6.12. This graph shows the overhang angle of each segment (blue) of each of the contour segments of the half cylinder geometry. As the half cylinder is being built, the overhang angle decreases and then returns to the original value given the geometry of the segments. The red curve represents the new torch angles that will be used for the particular overhangs based on the correction function. As mentioned previously, the greatest deviation should happen around 25° of overhang, which is illustrated as contour 38. The original overhang calculation at this point is 26.61° , and the corrected overhang value ends up having a torch angle of 35.3° .

While the corrected ideal torch angle was generated from few points, the maximum torch angle change is almost 10° of change. A change of this magnitude should be significant on producing near net geometry. From previous experiments, it was seen that 5° of torch angle change was responsible for being able to complete the complex part NGA section from

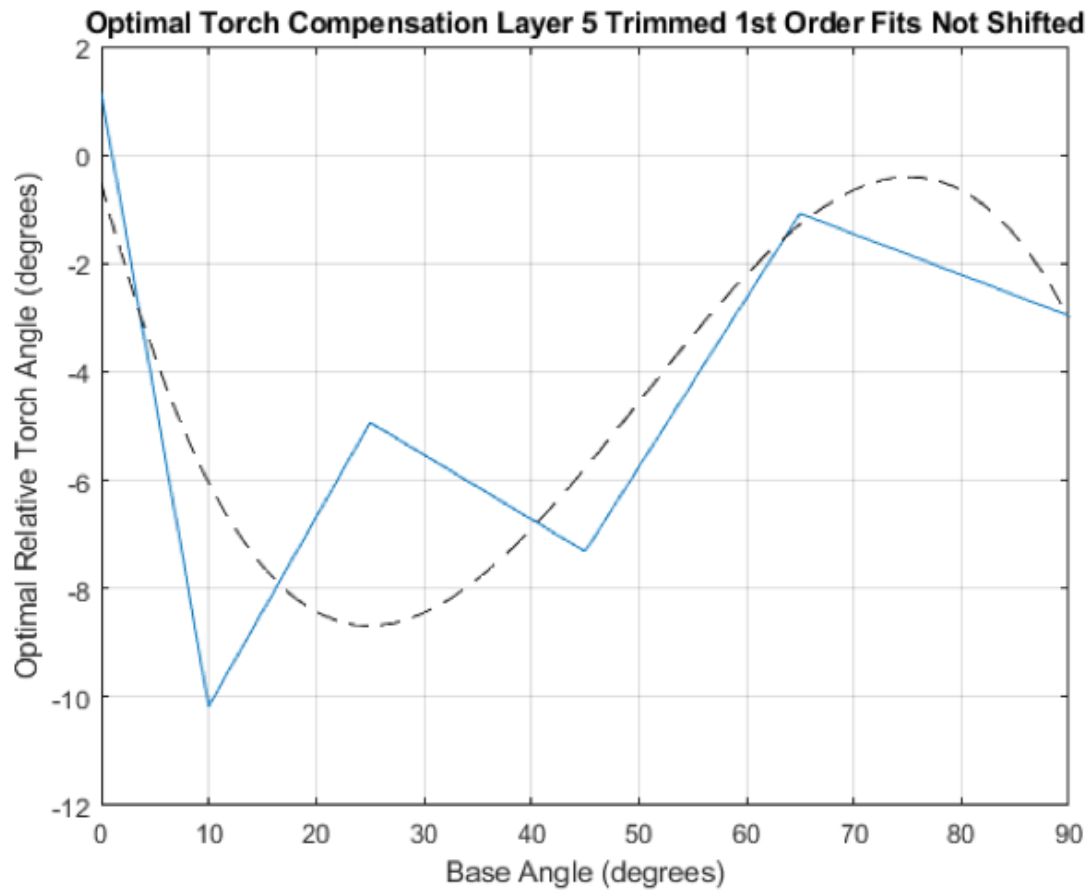


Figure 6.11: The 3rd order polynomial fit with the ideal zero points plotted against each other. The ideal polynomial will be used to give the appropriate overhang correction value for another overhang part.

Chapter 3 and reduce the humping mechanism seen on the horizontal overhangs. Ideally the effectiveness of these torch angles will be very evident from deposition through analysis of the full net surface when compared to the original build. If the geometry deviates further from near net shape without the correction, then the results of the corrected torch angle can be expanded and implemented on other geometry.

6.3 Demonstration of NGA Methods and Results

6.3.1 As-Printed Corrected Half Cylinder

The corrected torch angle half cylinder geometry has the same number of layers and positions as the previous demonstration in Chapter 4. The same contours were used that were generated from the CAD model and there was a 30 second wait between deposition of each layer. The only thing that was different is the applied torch angle corrections detailed in Figure 6.12. The relevant setup can be seen in Table 3.2 and the material is the same described in Table 3.1. The total build time was around 2.5 hours and had to be re-homed about 60% through the build due to the rapidly changing stick out size. The final results of the build can be seen in Figure 6.13².

6.3.2 Corrected Half Cylinder Metrology

After building the part, the geometry was scanned with Arctec Spyder camera and pulled into GOM Inspect for analysis. The geometry was compared against the expected CAD used for building the path plan of the part, which is the same analysis done for the previous half cylinder geometry. A summary of the metrology analysis can be found in Appendix C. A summary of the main issues with the geometry can be seen in Figure 6.14.

The results of the metrology point to a major issue in using the open-loop NGA methods to help compensate for overhang effects. The first half of the part looks great, and has arguably a better near net shape when compared to the original half circle. Particularly for the interface of the initial GA layers to the NGA section, the layers seem to be much closer

²For a video of the full build: <https://youtu.be/Y1tvHyYoWfo>

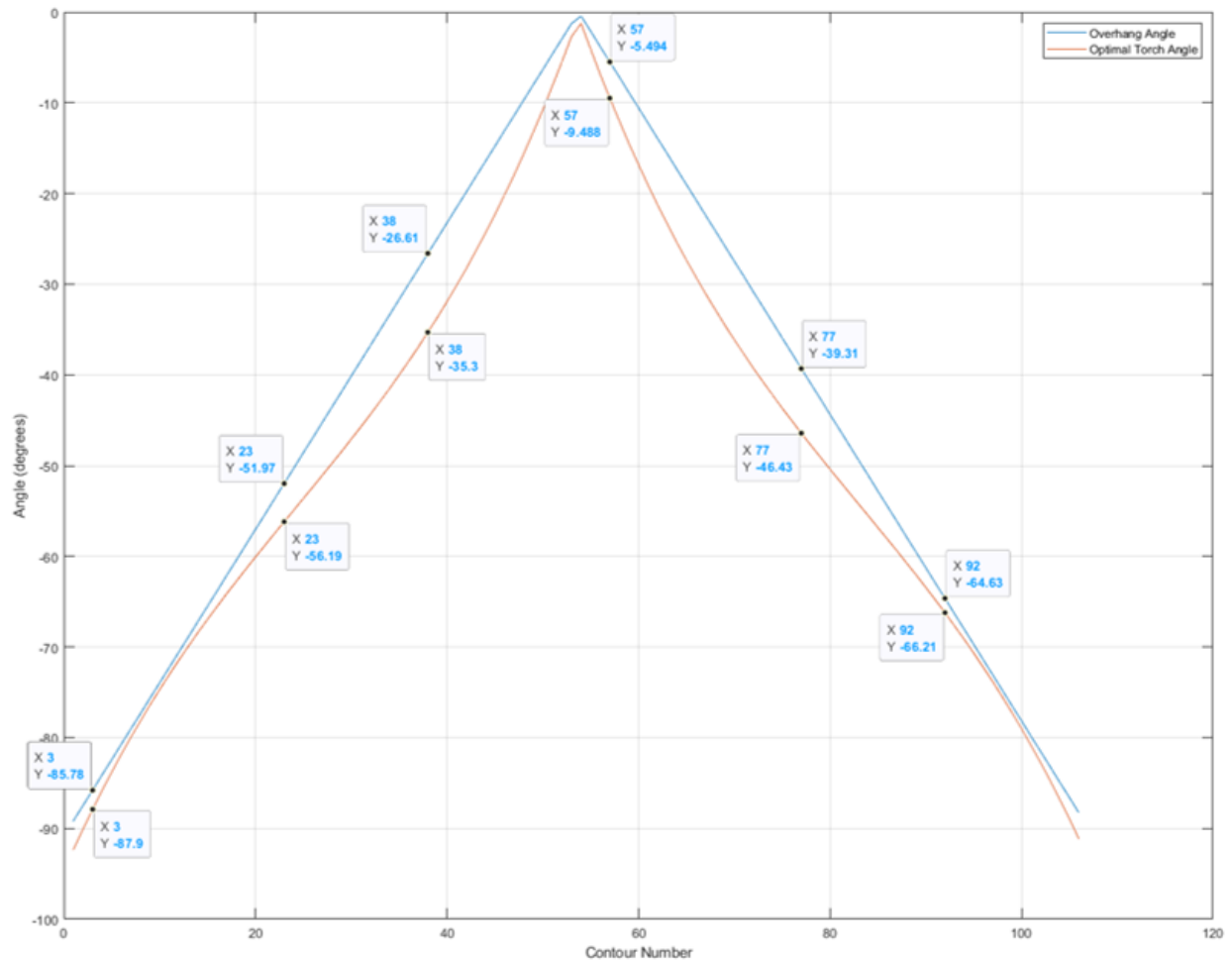


Figure 6.12: The graph shows the contour number versus the angle. The Blue is the calculated overhang torch angle and the red is the new torch angle based on the correction value applied from the correction function.



(a) Front View



(b) Side View



(c) Back View

Figure 6.13: as-printed condition of the corrected half cylinder geometry

to near net shape and the small torch angle change seems to have helped push the layers up to the correct location. However, halfway through the part, the layers become very erratic and begin compounding error. The location at which the error seems to begin is where the torch is rotating the opposite direction of NGA. Roughly 20 layers after the mid point at 60% through the build, the robot TCP had to be homed as the stick out was becoming greater than 1 inch and long arcing and causing instability in the weld pool. The stick out had rapidly changed and become much greater as the geometry was deviated significantly towards the back of the part. The results of the metrology clearly illustrate that these wire stick out changes impacted the near net shape of the geometry not only on a layer level, but for the entire upper half of the cylinder section. While the errors are significant, they can be tied back to a few reasons beyond the scope of the experiment.

6.3.3 Main Sources of Error in Corrected Half Cylinder

After further investigation and experimentation, the errors that resulted in the poor as built geometry of the corrected half cylinder can be tied back to poor process control and lack of correction capability. The errors are interconnected with the welding process, and could possibly be improved upon by real time control or process monitoring. The errors seem to have compounded on each other, making other errors arise during the build that had not been seen previously. To confirm that the results were not errors with the specific welding process, a second half cylinder that did not have corrected torch angles was rerun. The result of the build were almost identical to the previous results from Chapter 4, meaning that the corrected torch angles are the main source of the poor near net shape of the corrected half cylinder³.

The first issue comes from the curve of the wire that was mentioned as a source of error in Chapter 4. The wire curvature resulted in issues with programming the robot TCP and it's execution throughout the build. The wire issues could have been the initial cause of issues at the turning point of the geometry, but it is unclear to what extent the wire curvature contributed to the overall failure of the build.

³For a video of the second half cylinder: https://youtu.be/AkYH_hJ1A4g

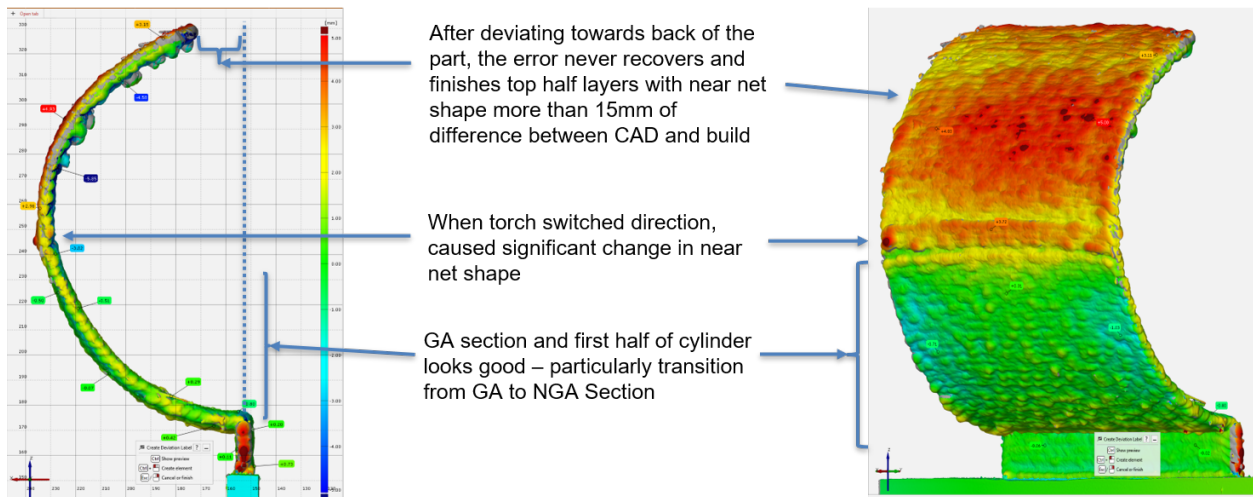


Figure 6.14: A summary of the major issues with the as built geometry when compared to the desired CAD of the corrected half cylinder. The issues seem to have begun and build up after the torch switched directions halfway through the build.

The second issue is related to the wire curvature, but more tied to the robot TCP. At the inflection point it seems clear that the correction angle caused the bead geometry to be pushed towards the back of the geometry. Given that no real time control was used to ensure layer height, there is a significant lack of layer height certainty. The rotation of the torch angle along with not having the expected material from previous layers means that the interaction of the weld pool on the geometry did not occur in an expected location. A generalized diagram of this error can be seen in Figure 6.15. The location was further back than normal, meaning that functionally the previous layer was not as tall as expected. The less height of the layer means that the contact of the wire to the geometry would have been further back than expected for the TCP location. This phenomena would also be exacerbated by the wire being curved, as if the wire curvature caused a change in location of the desired vs. actual location of the weld bead.

The results of not having fine control over ensuring that the existing geometry and TCP were matched up correctly for this build caused an error that kept compounding to the point where the upper geometry completed, but with significant geometry changes. The reason that this build was much more unsuccessful when compared to the original geometry is tied back to introducing the torch angle corrections for the half cylinder. For the first half cylinder build, the perpendicular angle to the previous layer ensured that if the layer deviated towards the front or back of the part that the next layers would push or pull the overall near net shape of the geometry back to a desirable state. The correction angles actually introduced error and instead of having the torch angle pull the geometry back, the angle became more steep on the upper section, making the error compound through lack of layer height TCP locations for the layer. If the paths had been perpendicular to the previous layer it can account for errors going in either direction by using the arc forces to direct the weld pool towards the TCP direction. In the case of the corrected half cylinder the weld bead was pushed too far outside, and instead of the previous layers helping fix the near net shape they directed the geometry further away from the desired shape until the error became too much to overcome. An general illustration of this phenomena is shown in Figure 6.16. Since this phenomena cannot be tested easily on the UTK system, it was desired that another

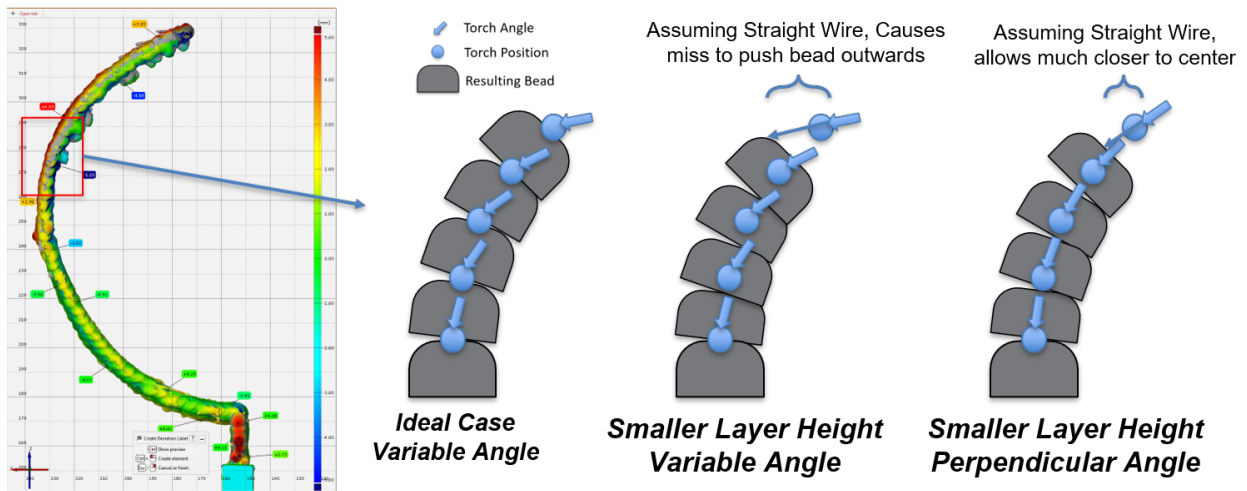


Figure 6.15: A summary of what a lack of layer height certainty can cause within a build. The variable angle used to increase the torch angle for the NGA methods pushed the near net shape of the geometry towards the back. A more perpendicular torch angle would have allowed the geometry to be more correct.

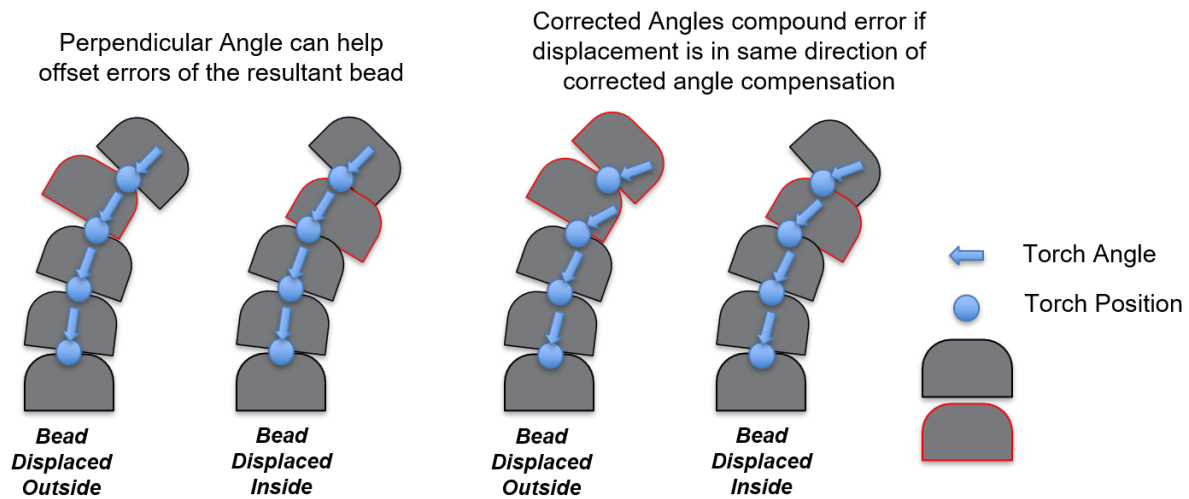


Figure 6.16: A summary of the compounding error seen in the build versus a more perpendicular torch angle. The correction to the torch angles to help compensate for gravity effects actually helped introduce error to the near net shape of the part.

WAAM system with better process control should try to use the NGA methods to see if it could help improve the effectiveness of the NGA techniques.

6.4 Application of NGA Methods on System with Process Control

As the UTK system did not have real time control capabilities readily available for builds, it was determine to try the NGA methods on a system with real time control but with a similar process. The metal Big Area Additive Manufacturing (mBAAM) group at the Manufacturing Demonstration Facility (MDF), a part of Oak Ridge National Labs (ORNL) had a notional tool mold geometry that they wanted to attempt without the use of a part positioner due to the complex geometry associated with the tool mold. A summary of the geometry and design can be seen in Figure 6.17. Before this geometry was built, the greatest overhang the mBAAM system had produced had been 20° for small segments. The face of this tool mold had overhangs up to 35°, and was completed without process change and only by modulating the tool on the overhang sections. The system is maintained and built by Lincoln Electric Additive Solutions and uses their own proprietary weld bead settings and layer height control[21]. The layer height control ensures a stable range for the expected height of the layer, giving a much stable process through the entire build regardless of weld settings and heat buildup within the part.

The MDF uses a custom slicing and path planning software used for the mBAAM system. A few modifications to their path planning software was necessary for integrating NGA techniques. However, given that the path planning software at the MDF contains a bead model, a similar overhang angle identification was used to designate certain bead segments for NGA corrections. A summary of the full slicing and a notional layer can be seen in Figure 6.18. The part was built in the direction seen in the figure from bottom to top. The purple segments are the bead paths where the geometry is identified as having an overhang that needs compensation. The material the notional tool mold was printed in was Lincoln

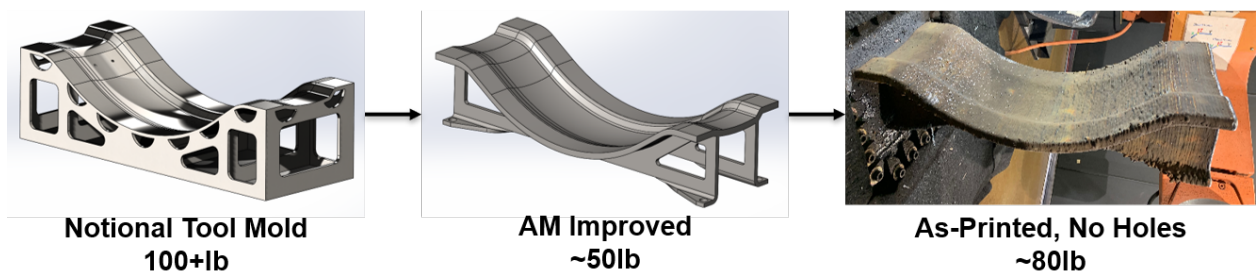


Figure 6.17: A summary of the Tool Mold geometry built with NGA Methods. The part was printed without the help of a part positioner, so a 35° overhang angle was built on the tool face.

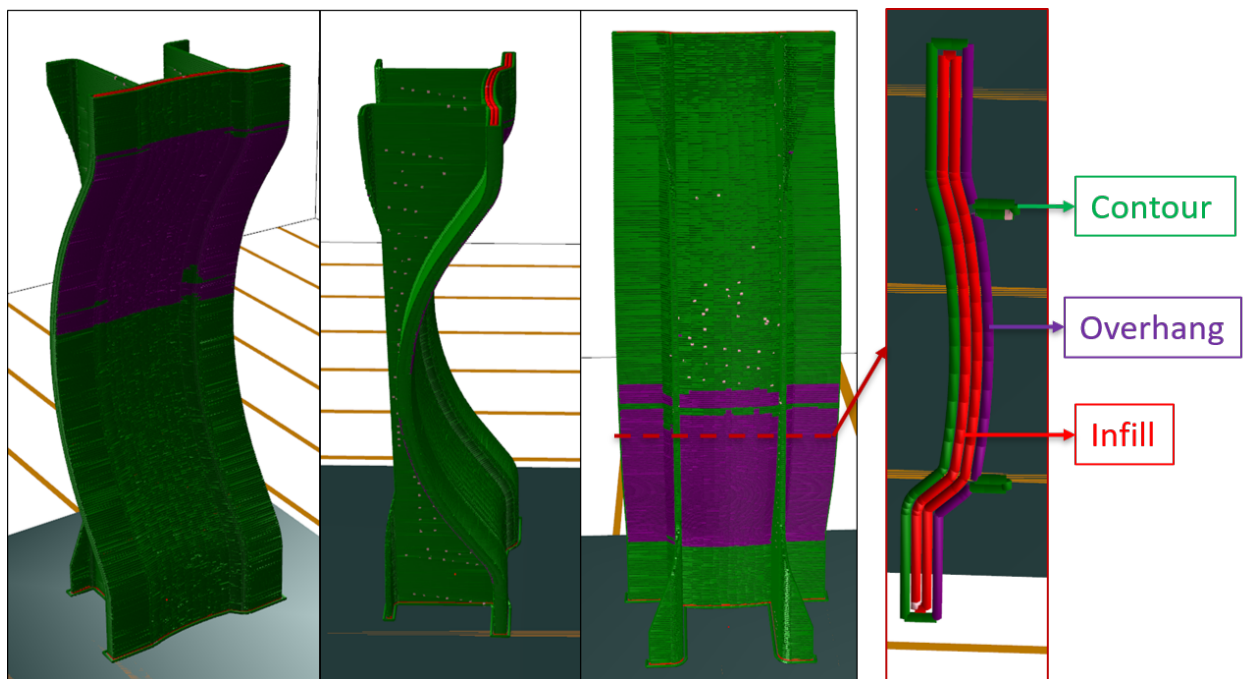


Figure 6.18: Pictures of the slicing and path planning associated with path planning in the MDF slicing and path plannign software. The segments you see are representative of the expected bead geometry. The purple sections represent bead segments which had a torch rotation applied to compensate for the large overhang in the build direction.

Electric LA100 of which the MDF has done extensive work on process settings and material properties [54].

For this notional tool mold geometry, every NGA segment was not planned perpendicular to the previous layer. Simplification of the process was used so only rotation torch angles of 10°, 20°, 30°, and 35° were programmed for the paths. A summary of the location of these torch angle changes can be seen in Table 6.3. These angles were applied manually based on measurements of the expected bead location center points to overhang angle. The manual override and assignment of torch angle was necessary for the first test of the overhang compensation using NGA methods. The angles were chosen as they are as close to perpendicular based on the previous layer as the bead center locations could be used to calculate. The lower threshold of overhang is 10° and the upper is 35° which is the maximum overhang the part design has relative to the build direction. The negative values are necessary because the tool mold could not be rotated on the base plate, and the torch needed to rotate towards and away from the robot to give the relative torch angles necessary for the overhang segments on the top and bottom of the geometry.

The results of the build and the analysis of near net shape of the part can be seen in Figure 6.19. The results were great for this tool mold geometry, with the maximum deviation being roughly 6mm on the NGA sections near the edges where the heat build up was the greatest. The heat build up on the edges combined with the torch rotation caused the weld pool to have excess flow. However, the near net shape for the part was achieved, roughly 15° more overhang than had been demonstrated on this system previously. Application of these NGA methods could also be greatly improved by implementing more appropriate torch rotation for each individual layer and by also determining a necessary path shift for the layers. The first attempt with a simplified use of torch rotation was very successful in extending the mBAAM system's capability of depositing overhangs to near net shape, and with only using simplified torch rotation. Ideally, the MDF can automate the NGA calculation and torch rotation into their path planning software for future builds and experimentation.

6.5 Implications for NGA Methods to Improve Near Net Shape of Overhangs

From the results of the corrected half cylinder, it is clear that using only open loop corrections to the path plan to help improve overhangs is not acceptable. However, before the half cylinder inflected the torch angle and exacerbated the displacement of the bead at the midpoint of the build, the near net shape of the bottom half of the half cylinder seemed better than the previous build. This is also confirmed by the results of the torch shift experiments, where for significant deviation changes the torch position compensation was effective. The WAAM cell at UTK used in the test matrix experiment did not have a stable enough process to give consistent experimental results. When a torch rotation is applied to a WAAM system like the mBAAM system at the MDF, the NGA methods greatly improve the near net shape of overhang sections. The process control associated with the mBAAM system provides the opportunity for the NGA methods to help use the arc forces to deposit the overhang layers without losing surface tension of the weld pool. These results have just been demonstrated for simplified geometry and NGA methods, and with more time and extensive experimentation should be able to be applied to any DED system where the torch end effector can be rotated to help compensate for gravity effects.

Table 6.3: Torch Angles Relative to GA

Torch Angle	Layer Number
0°	0-34
10°	35-36
20°	37-41
30°	42-46
35°	47-82
30°	83-103
20°	104-128
10°	129-139
0°	140-163
-10°	164-175
-20°	176-200
-30°	201-223
-35°	224-257
-30°	258-262
-20°	263-267
-10°	268-269
0°	270-296

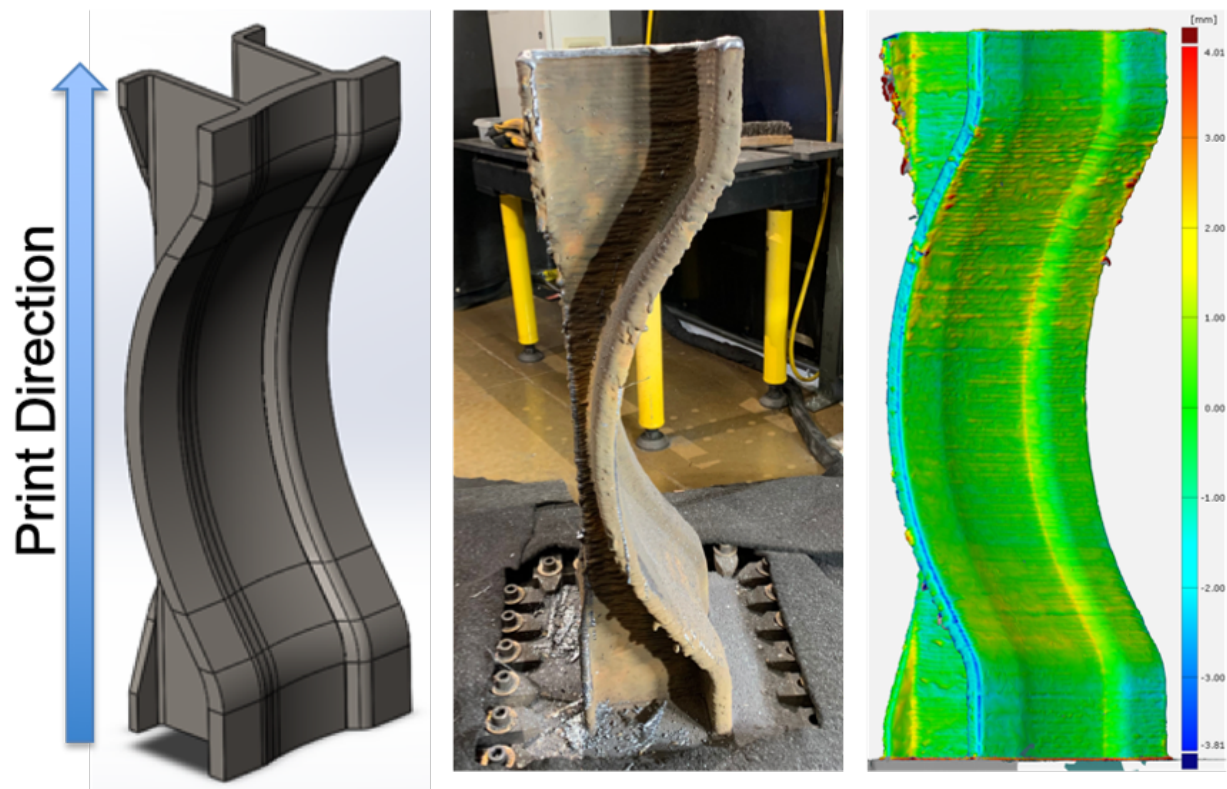


Figure 6.19: Final results of the the notional tool mold geometry. The sections where the NGA of the part is located is rougher than the rest of the tool surface, but near net shape was achieved for the geometry without the use of a part positioner.

Chapter 7

Simplified Thermal Modeling for Path Planning

From the previous work on NGA methods, what has become more apparent is the need for stable process parameters to effectively plan and deposit material. Bead geometry is greatly affected due to heat transfer of the welding process. Maintaining the surface tension required for NGA methods can be tied directly to the temperature of the process. The work presented in this chapter focuses on development of a thermal model for prediction of the temperature of a build based on the spatial positioning and process settings. The spatial position in time and space is dictated by the path planning software, so with a sufficient thermal simulation, the heat transfer results could be used to influence better or more effective path planning strategies. The path planning simulation should be another tool for a part designer to use in developing the tool paths and path planning strategy for builds by analyzing hot spots which could cause the resultant bead geometry to not behave as expected. A simplified lumped mass model includes heat conduction between the deposited lumps to observe the effects of path planning changes on the expected temperature evolution of the part during the build.

7.1 Theory

From the previous results regarding NGA techniques, the number one priority is ensuring that ideal thermal conditions are met that allow the weld pool to maintain the surface

tension necessary to deposit in the NGA orientations. Given that the intention of using NGA methods is to reproduce geometry that is deposited GA, it would be desirable to have a tool integrated into path planning which allows prediction of where meltdown or conditions where the NGA methods may not be able to occur due to overheating. A thermal simulation can be used to help make corrections to the build plan by monitoring the inter-layer temperature as well as the overall thermal buildup over the course of long builds. Path planning information contains position, orientation, and speed which are the spatial components necessary for building a thermal prediction based off of material and process settings. Table 7.1 details the 6 necessary planning inputs that can be accounted for in the CAD to Part framework. The only missing detail is the relevant material properties of the deposited metal.

Since the CAD of the desired part is known, a 3D thermal prediction can be made from all of these parameters. [56] attempted to find temperature, residual stress, and distortion. However, the simulation time required days to complete for the full geometry. This long period of wait for a simulation to finish is not acceptable for use as a path planning tool. A high level of fidelity is not needed for the analysis for predicting temperature for NGA methods. Realistically, an idealization of the hot spots or the max temperature that the part would experience would be more than acceptable for this analysis. Simplifying data like the work done in [13] also shows that the peak temperature seen by a DED AM part dictates the resulting thermomechanical properties to an acceptable degree of accuracy. The simplification also holds true for NGA methods: If the weld bead is too hot, the surface tension forces cannot be maintained before the weld pool solidifies into acceptable geometry.

Therefore, it was speculated that using the organization of the path planning framework from Chapter 5 and appending the properly sequenced energy inputs from Table 7.1 might provide useful information to predict thermal evolution during the CAD to Part design process. A similar method from [45] was used to segment the part into superlayers of heat buildup that experienced the heat transfer for the superlayers at the same time. The methods presented in this work takes this idea by segmenting the layers into lump mass experiencing heat transfer by activating an internal heat generation for the lump defined by the energy input from a welding torch. The simplification of a moving heat source in space defined by

Table 7.1: Variable Path Planning Inputs

Spatial	Energy
Position	Voltage
Orientation	Current
Speed	Mass Input

the CAD and torch trajectory will hopefully provide a solution to help with path planning and predicting potential over heating within the path planning software.

7.1.1 Thermal System Concept

The general assumptions for the current lumped thermal model are as follows:

- Thin wall geometry where the bead height and width will be used to determine the thermal mass for arbitrary lump sizes.
- The thermal system originates on a base plate at ambient temperature which is experiencing heat convection transfer to the air.
- The lumped thermal mass, which is a voxel of material that has been deposited or is being deposited, experiences heat conduction to its neighbor or the base plate. Convection and radiation pathways for the lumped thermal mass are not included.
- The welding heat input is generalized as an internal heat generation for the specific lump activated at the time when the lump is deposited.

The assumptions were imposed to simplify the mathematics and computational requirements of an emerging part build with the hope that the thermal simulation could function reasonably within the overall CAD to part design timeline. The goal of the software is to provide a quick, semi-accurate simulation which can be used to qualitatively assess a path plan to ensure that meltdown of the part will not occur. The fundamental governing equations will be broken down below.

For a simple three dimensional voxel that makes up a portion of geometry, consider the basic heat transfer equation 7.1. The equation shows the directionality of the heat flow in the x, y, and z direction. Consider from our path planning inputs that we know the spatial and energy information for the torch and the current CAD of the part. Therefore, the entire part can be voxelized and the heat energy input between each can be characterized by equation 7.1 where u is the energy input and α is the thermal diffusivity of the medium.

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = \frac{1}{\alpha} \frac{\partial u}{\partial t} \quad (7.1)$$

We wish to equate the change in thermal energy to the heat flux out of a square plane at $x = a$ and $x = b$. To do this we use **Fourier's heat law** which states that the conduction flux density of thermal energy, $q(x, t)$ is proportional to the temperature gradient,

$$q(x, t) = -kU_x, \quad (7.2)$$

where the negative sign reflects the fact that heat flows from hot to cold, just as in Newton's law of cooling, with a constant of proportionality, k , called the thermal conductivity [(energy·length)/(degrees·time)]. Equation (7.2) can then be solved along the plane described by a and b defined in every direction. For the simplified analysis, inspiration on simplification of the thermal effects to be conduction between the lumps is taken from [46]. The conduction between lumps can then be described by Equation (7.2) between the lumps from the current layer, and the lumps from all the previous layers. A generalized breakdown of the simplifications of the conduction heat transfer for a layer and node can be seen in Figure 7.1.

A simplified lumped model allows the highly complicated non-linear partial differential equations of the complete heat transfer situation to be simplified into mass lump like similarly prescribed in [45]. The lumps can also be tied to the waypoint information from the path planning software in the future for more automated analysis. The path planning software can be modified to assign the necessary thermal properties and spatial activation properties to ensure the heat source is moving and the heat transfer between the nodes is correct.

7.1.2 Thermal Prediction Governing Equations

Welding literature includes the ASME standard for predicting welding heat input as seen from [34]. The heat input can be calculated from the voltage, current, and travel speed of the weld. The equation for heat input due to welding parameters is defined in Equation (7.3). The estimation is based on standards set out for welding, and these values can be pulled from the path plan of the part.

$$\dot{Q}_{torch} = \frac{Voltage * Current * 60}{TravelSpeed} \quad (7.3)$$

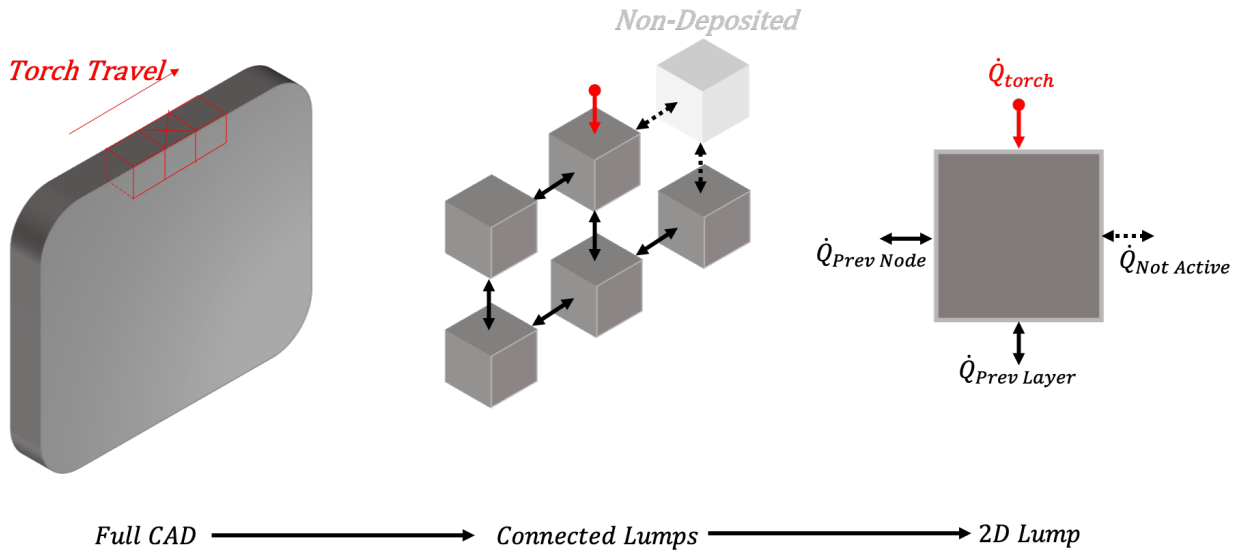


Figure 7.1: A summary of the generalized representation of the thermal equations used for the simplified thermal prediction of WAAM. The lumps experience conduction down to previous lumps and forward and backward as they are deposited spatially.

While Equation (7.3) is used for standard welding applications, standard welding processes do not efficiently distribute all heat into the melt pool. [35] discusses that only a certain percentage of the GMAW and/or GTAW processes input energy into the base material. For MIG processes, it has been reported that it can fluctuate between 50-75 percent of the expected heat input. Since the efficiency of the process is vital for total heat transfer, it needs to be accounted for in the constitutive equations. The efficiency of the process can be applied to the instantaneous calculation for heat transfer as seen in Equation (7.4).

$$\dot{Q}_{total} = efficiency * \frac{Voltage * Current * 60}{TravelSpeed} \quad (7.4)$$

Once the heat input can be calculated for each time step, the next main heat transfer method is the effective total heat loss of each lump due to the fundamental modes of heat transfer and change of state from liquidus to solid metal. Simplifying the conduction lumped model will be taken from Equation (7.5) for the differences between the lumps. The general equation for conduction heat transfer between lumps can be defined as:

$$\dot{Q} = \frac{T_1 - T_2}{\left(\frac{L}{kA}\right)} \quad (7.5)$$

In the lumped model parameters, the surface will be made up of elements that interface with each other. The part will conduct through each one of the lumps which means 7.5 can be modified to:

$$\dot{Q}_{wall} = \frac{T_{current} - T_{next}}{\left(\frac{Length_{lump}}{kArea_{lump}}\right)} \quad (7.6)$$

While the governing equations are relatively simple, the total number of equations can add up based on the size and number of the lumps. However, the simplified nature of the heat transfer methods is expected to be accurate enough to estimate the heat build up given an appropriate lump size. Generally, for the purposes of a path planning tool it is desirable for the simulation to run in a few minutes or less. The number of lumps for an arbitrary

thin wall structure is chosen at the discretion of the user, meaning that the length of the node can be defined in Equation (7.7):

$$Length_{lump} = \frac{Layer\ Length}{Number\ of\ Lumps} \quad (7.7)$$

Since the number of lumps is variable, this also means that the speed at which lumps are deposited changes. The speed at which lumps are deposited also effects the heat transfer methods based on the indicated travel speed. Equation (7.4) describes the total heat input for a weld based on the travel speed, which cannot be used at any instantaneous point for the heat transfer calculations of heat input. After a number of lumps has been assigned which dictates the node length, the instantaneous heat input can be defined as seen in Equation (7.8) below:

$$\dot{Q}_{instantaneous} = efficiency * \frac{\frac{Voltage * Current * 60}{TravelSpeed}}{Length_{lump}} \quad (7.8)$$

Therefore, at the moment of deposition and until the next lump is deposited, the lump is depositing this amount of heat. The deposition for this simulation is defined as the "activation time" for the lump. The simulation software ties spatial parameters to the lump size, allowing the user to modify lump sizes and activation times accordingly. What this means is that effectively the lump has internal heat generation equal to the expected welding heat input for the amount of time the torch would pass over that lump. The lumps can then be built and activated as the torch spatial parameters would dictate from a path plan. The result is a moving heat source based on arbitrary lump size that represents the torch moving in space. A generalized figure of the activation can be seen in Figure 7.2. The size and length of the wall is arbitrary, but the greater number of lumps and/or layers means more heat transfer equations that must be solved.

The heat of latency due to phase change is incorporated through adjustments in the magnitude of the efficiency value in Equation (7.8). For welding, since the weld metal enters the weld pool as a liquid and then solidifies, there are heat losses due to phase changes and the associated latent heat. The efficiency value is used to account for these changes for the system.

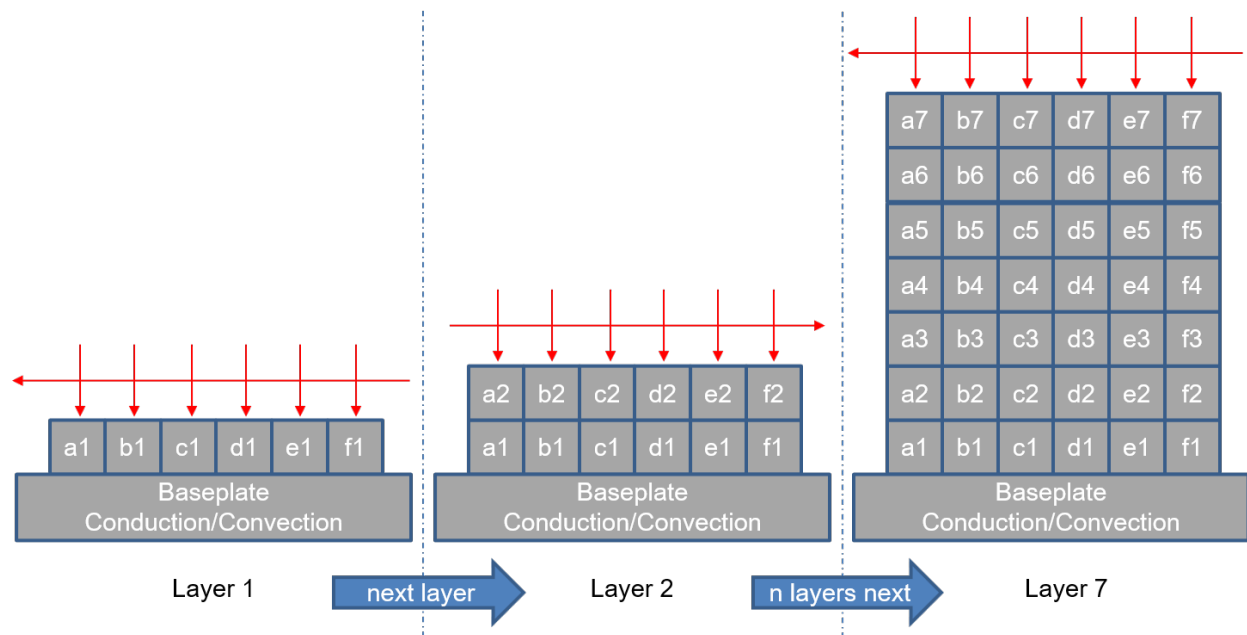


Figure 7.2: A summary of how the lumps are decimated according to activation and torch travel. The layers are designated as numbers and the lumps as letters. This can be repeated for any number of layer of walls.

7.2 Implementation of Heat Transfer Methods

Now that the general methods have been established for the thermal prediction, the next step was implementing these methods in software. The core issue with implementation lies with keeping track of the heat transfer methods between each node and how those nodes effect the nodes around them, particularly with a moving heat source and activation of the nodes. For first steps of implementing the lumped parameter method means that significant assumptions were made for the purpose of actually integrating the simulation in MATLAB.

7.2.1 MATLAB and Implementation of the Node Activation

For the MATLAB PDE toolbox to be used, the partial differential equation must have the full geometry and thermal properties defined for each node before the simulation can be completed. For analysis purposes, only thin 2D walls with square aligned lumps were generated for simplified analysis. Each of the walls have lumps that are directly interfacing sideways and upwards with another node, like seen in Figure 7.1.

The geometry for the PDE solver to work needs to be defined before the simulation can be solved. This means that even though a node has not been activated that it still has the conduction between lumps already defined and acting on the system. An activation function was developed to approximate a "weld" lump being deposited at the appropriate time step. At every iteration of the solver, the activation function goes to a lookup table of the activation times to see which nodes have a thermal conductivity of zero (which means the lump has not been deposited) or a thermal conductivity of the as-deposited material (which means the lump has been deposited). The activation of the nodes also coincides with the node experiencing heat input from welding. The MATLAB code for these activation functions can be seen in Appendix D.3. The times of node activation are predetermined based on welding speed and lump size. A matrix of these values is used when heat input and the appropriate thermal conductivity is activated.

7.2.2 Simulation Parameters

For the work presented in this section, there were a few simulation parameters that were assumed or implied. The value of these parameters can be seen in Table 7.2. These values are taken from the material properties of low carbon steel. The main purpose of this code is to provide a tool for displaying the expected temperature of a lump, so some of the parameters were assumed to help provide a more useful analysis. One of the main assumptions is having a natural convection parameter out of the simulated base plate. The natural convection is only occurring on the edges of the base plate out into air. If there was no heat escaping from the base plate, the conduction simulation would only continue to build up, skewing results of the simulation for analysis. The convection experienced by the base plate is only around the edges, allowing some heat to dissipate out of the system as it would behave in the real world.

Given the parameters and constitutive equations have been met, simple thermal simulations need to be realized to provide qualitative and quantitative analysis. The goal is to show that changes to spatial relationships of the heat source can result in hot spots or indicate sections where heat buildup can occur. Simplified 2D geometry will be used to establish the effectiveness of these methods before moving to more complicated 3D representations.

7.3 2 Layer Wall Examples

The first test of the lumped thermal simulation is to see if the simulated temperature behavior changes with small changes to the path plan for a simple geometry. Four two layer walls were considered, all simulated with the shared parameters seen in Table 7.2. The four walls are designated by their identifying path differences: Same Direction, Alternating Direction, Slower Travel, and Faster Travel. The nodes and their points are referenced in Figure 7.3. The nodes are named the same, but varying paths and timing settings are used to identify temperature values.

Table 7.2: Constant Simulation Parameters

Density	7870 kg/m^3
Specific Heat (C_p)	$510 \text{ J/kg} \cdot \text{K}$
Thermal Conductivity (k)	$45 \text{ W/m} \cdot \text{K}$
Ambient Temperature	293 K
Voltage	15 Volts
Current	80 Amps
Efficiency	$.5 \text{ percent}$
Base Convection Coefficient	$50 \text{ W/m}^2 \cdot \text{K}$
Bead Height	2.25 mm
Bead Width	6 mm
Base Dimensions	$152.4 \text{ mm} \times 304.8 \text{ mm} \times 25 \text{ mm}$
Layer Wait	60 seconds

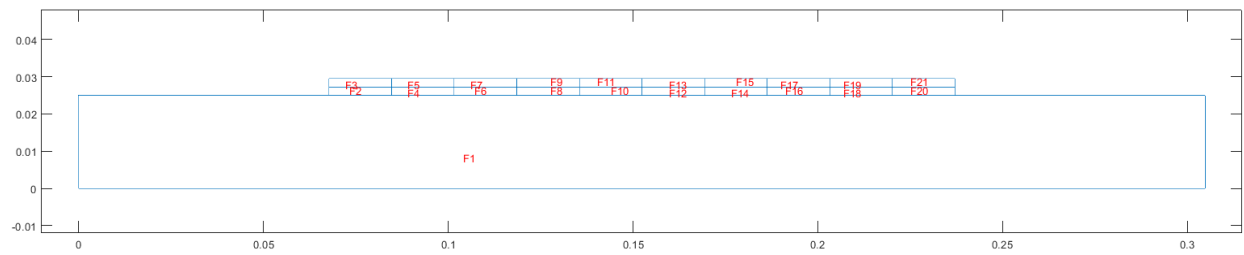


Figure 7.3: A summary of the wall configuration used for analysis. The numbers represent the lumps that the conduction occurs between. The X and Y axis are in meters for the simulation.

7.3.1 Change of Direction for 10 Lump Layer Simulation

The initial simulation is a path of a two layer wall where deposition goes the same direction. A second simulation was run where the first path runs exactly the same as the first, but then reverses direction of deposition for the second layer. The builds are centered on the base plate. The travel speed for the torch was set to 2.75 mm/second to generate the paths. The number of lumps for the simulation was set to 10 per layer. The total simulation time was set to 240 seconds¹.

To perform a more specific analysis, the temperature of these simulations can be extracted. The first quantitative measurements is the maximum of the simulations. The maximum temperature is above 2,000 Kelvin which is above the melting temperature of this material. Obviously these simulations are approximate due to the assumptions within this work, but this temperature is not too far above expected melting temperature. The maximum temperature value of the same direction simulation is 2013.7 Kelvin, and the maximum temperature of the alternating direction simulation is 2021.3 Kelvin. While not a significant change, it does show that alternating direction of the second layer passes over a hotter section earlier, giving a higher peak temperature. However, given that both of these maximum temperatures are much hotter than the melting temperature of the chosen material, these quantitative results are limited. However, qualitative analysis of the simulations yields some interesting and useful insights.

Figure 7.4 shows the end of the alternate direction simulation after both layers have been deposited and the heat transfer has reached equilibrium². Looking at the figure, it is almost impossible to tell which direction the wall was deposited. Since the direction of each layer was alternated, it resulted in a much more even distribution of the heating effects along the wall, even for just two layers.

The end frame of the simulation with both layers deposited in the same direction can be seen in Figure 7.5. The change is subtle, but there is definitely a skew in the heat distribution towards the right side of the part. Due to the heat being pointed in that direction, the heat stays concentrated on the right side as it is built up. The same effect was seen in Chapter 3

¹A video of the same direction simulation can be seen in <https://youtu.be/qoqjkY6I5rc>

²A video of the alternate direction simulation can be seen in <https://youtu.be/4hz4g0aGchc>

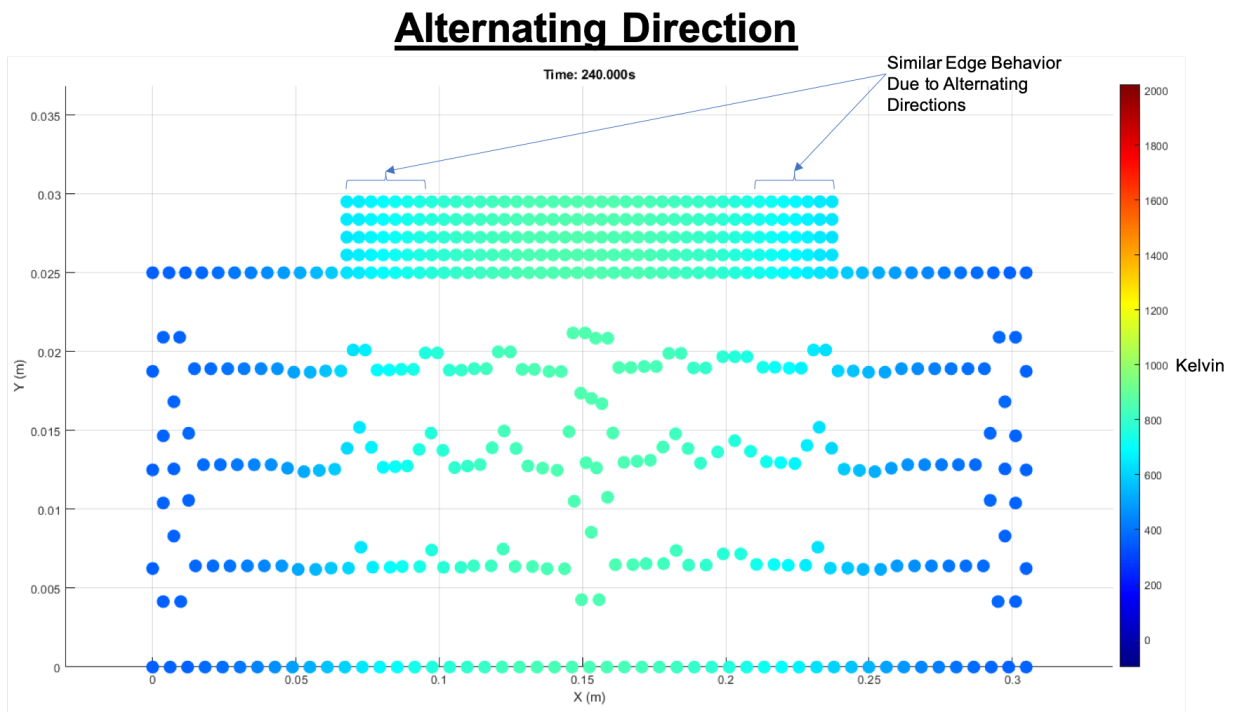


Figure 7.4: An end frame of the nodes that the simulation uses for calculation of the lumped parameter thermal model. The results show a fairly even heat distribution after both layers have been deposited.

whenever the layer direction was not alternated and heat would buildup on the end of the part and cause the part to fail. This is a qualitative indicator that the lumped conduction model is showing expected physical results. Simply put, while the quantitative values of this modeling technique are limited, qualitative results show expected behavior of the thermal behavior of the deposited section.

7.3.2 Change of Speed for 10 Lump Layer Simulation

Since there was a slight difference in the qualitative results of the simulation comparison, the next step was to see if inducing a change to the heat input timing would result in a similar qualitative effect. Therefore, two new simulations were run using similar parameters but with a change to the speed of the torch. Both a faster and slower torch speed were considered for this analysis. These simulations also used 10 lumps per layer with identical simulation time.

Quantitative analysis of the faster and slower torch speeds also yields results that match with physical effects seen in WAAM. The maximum temperature of 2mm per second travel speed was 2397.6 Kelvin, much higher than the previous two simulations. This is expected because the torch is spending a much longer time in certain areas putting material and heat into the area. The maximum temperature of 3mm per second travel speed was 1972.3 Kelvin. This also matches to expected physical effects since the converse is true with the torch spending a lot less time in areas imparting the heat transfer effects of welding. These qualitative results show promising results for using this type of thermal modeling to help identify areas where torch velocity and process settings could result in meltdown. While the quantitative results are still very high, this is expected since only conduction effects are being accounted for and not the effects of convection and radiation that would be present with this system during WAAM.

7.4 Comparison to In-Situ Thermal Camera

Once the result was been qualified, a 30 layer GA wall was built that alternated direction. A FLIR A35 thermal camera was trained on the part during the build to record the temperature

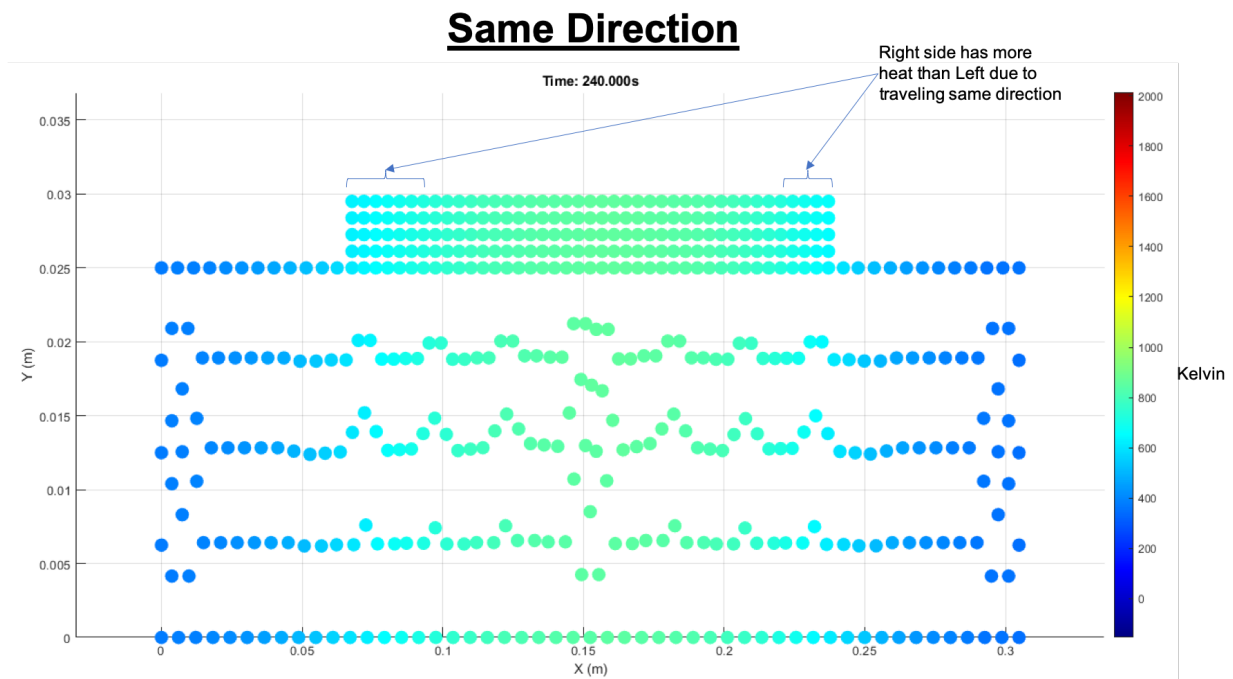


Figure 7.5: An end frame of the nodes that the simulation uses for calculation of the lumped parameter thermal model. The results show that the heat is more skewed towards the right side.

of the build. If the results from the in-situ monitoring can be seen to match up similarly to the simulation, the simulation results can be considered successful.

The FLIR data needs to be correlated to the simulation in terms of location and layer, so 21 points were selected with 3 being on a layer during the build. The points and the IR setup can be seen in Figure 7.6. The points were chosen by hand and are associated with the following layers as shown in Table 7.3.

After identifying and extracting the temperature data from each point for the full build, the temperature curves can be plotted for each point. A summary of each point's temperature curves can be seen in Figure 7.7. Looking at the curves, the thermal behavior of each point is very apparent on where the point lies within the layer. The edge points have alternating temperature peaks associated with the alternating direction of each layer. All of the middle points have a steady peak oscillation due to the torch passing back and forth. What is very apparent is that the saturation of the camera is happening for each layer, as even the top layers see a temperature blip from the torch being turned on based on the temperature curve. In fact, analysis of the waves in MATLAB findpeaks command shows that almost every curve can find all 30 peaks due to the torch passing directly above, below, or in line with the reference point.

Therefore, a 30 layer alternating wall with 10 lumps per layer was run with the expected welding speed of 2.75 mm/s along with all of the parameters found in Table 7.2. The simulation for a 30 layer wall with the heat generation and thermal conductivity activation functions took multiple hours to run to complete. The results of this 2D approximation are even more incorrect than the ones seen in the 2 layer wall simulations. There are expected temperature values of greater than 5000 Kelvin for this simulation which is physically impossible. What is very clear with the increase in the number of layers is that the lack of models for a free convection and radiation dissipation into the environment limits the quantitative simulation accuracy. The more layers that are deposited the more the heat builds up within the simulation, resulting in results which are not physical possible.

Table 7.3: Points on the 30 layer wall used for analysis

Layer 1	Point 1, 2, 3
Layer 5	Point 4, 5, 6
Layer 10	Point 7, 8, 9
Layer 15	Point 10, 11, 12
Layer 20	Point 13, 14, 15
Layer 25	Point 16, 17, 18
Layer 30	Point 19, 20, 21

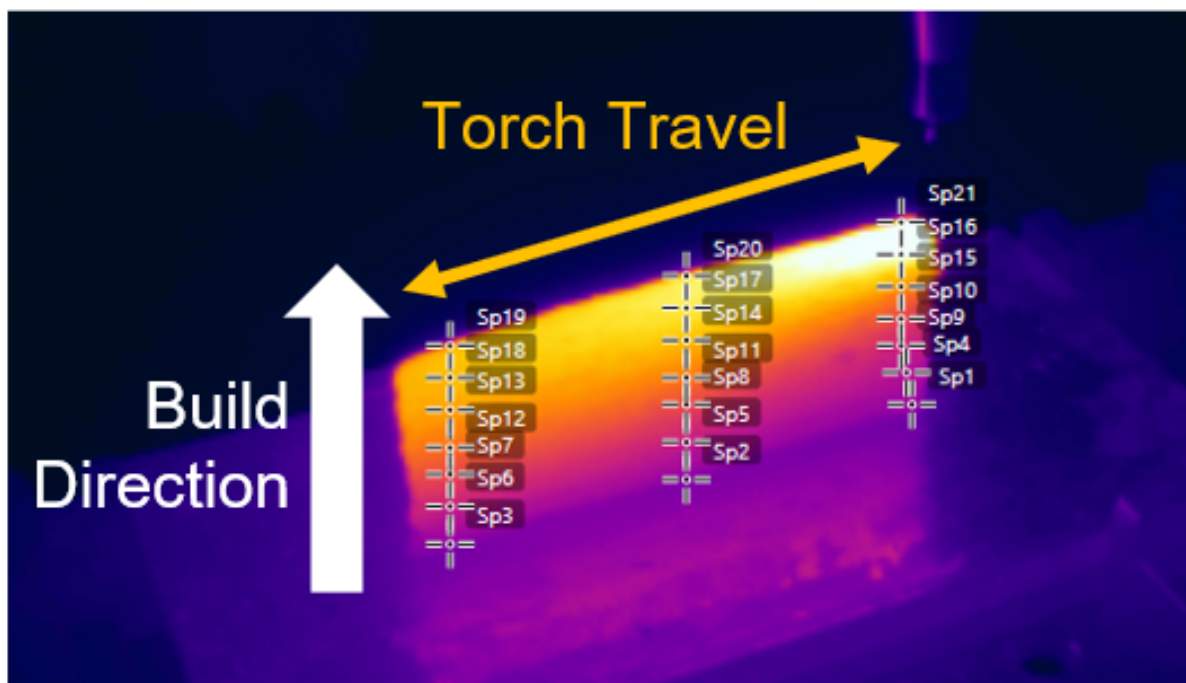


Figure 7.6: A picture of the FLIR data extracted for comparison to the simulation. The points were chosen to have 3 points: one in the beginning, middle, and end of a layer.

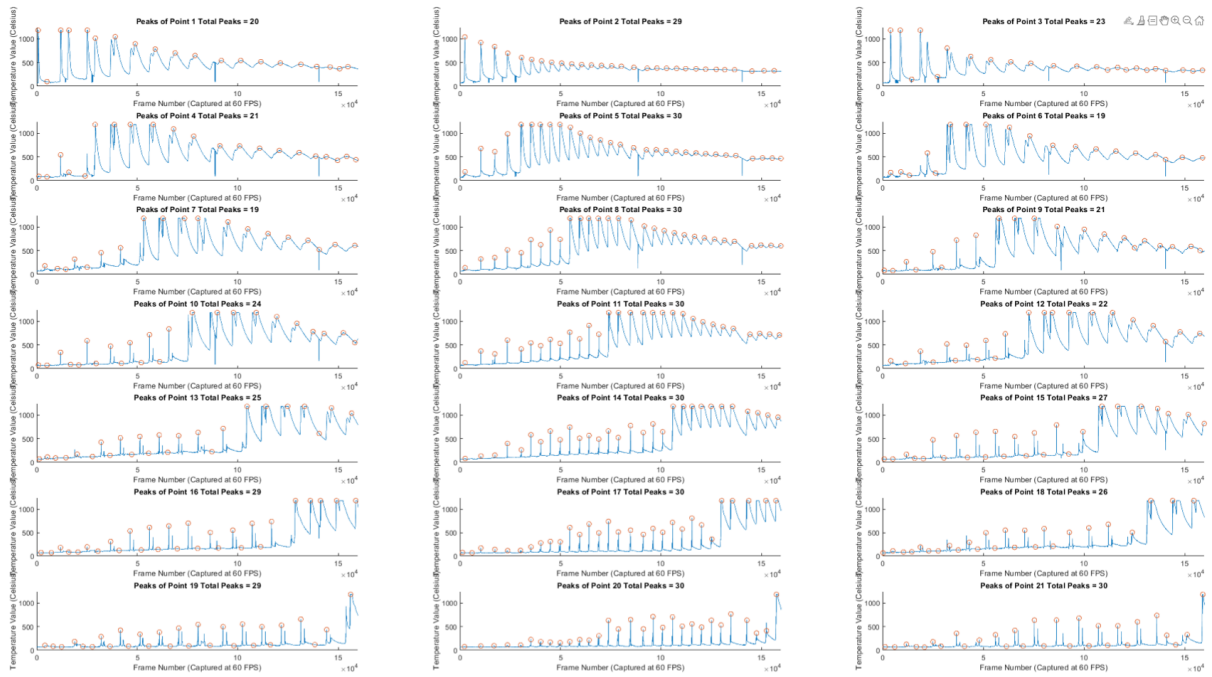


Figure 7.7: The extracted point's temperature curves over the whole build. The oscillation of the layers and the peaks can be seen easily with an in-situ thermal camera.

7.5 Implications of the Lumped Parameter Modeling

The results of the research in this chapter have revealed that as it currently resides, the lumped conduction simulation is not adequate for quantitative analysis of WAAM. However, results are promising from a qualitative perspective towards these methods being useful in predicting heat build up locations and trends. The key challenge lies in the integration of a moving heat source and activating nodes using their thermal conductivity to have a node initiate heat conduction transfer. The simulation method also requires a significant amount of computation time, as shown in Figure 7.8. The graph shows simulations of 2, 5, 10, 20, and 30 layers with various settings disabled or enabled for timing. Up to 10 layers does not have a significant amount of deviation from each other, but once 20 and 30 layer simulations are required, the time exponentially increases. The number of lumps per layer seems to be tied the most significantly to increasing simulation solving time, but the heat generation function and the activation functions are also causing a huge drain on the solver's resources. When the activation function was disabled the simulation time reduced considerably.

Another significant issue is the heat build up due to conduction without accounting for the convection and radiation, the primary heat loss channels. Conduction heat transfer is the greatest mover of heat into the previous structure, but as the part grows allows more convection and radiation to occur on the surface area of the as-deposited structure. The simplified model does not account for these effects, which continues to grow as the part gets bigger. The results of these simulations indicate that even for smaller features that conduction and/or radiation heat transfer must be brought into the model. Not including these heat loss pathways certainly contributes to the unrealistic temperature build ups seen in the simulations.

Future work should focus on using a more appropriate PDE solver software than MATLAB to improve speed and efficiency of the simulations. Qualitatively the effects of changing speed and direction as it relates to the heat transfer of the part can be easily seen with these methods, and its possible with some modifications that the modeling can be used as a simple prediction tool. However, at the current state this method does not seem feasible due to significant computation time.

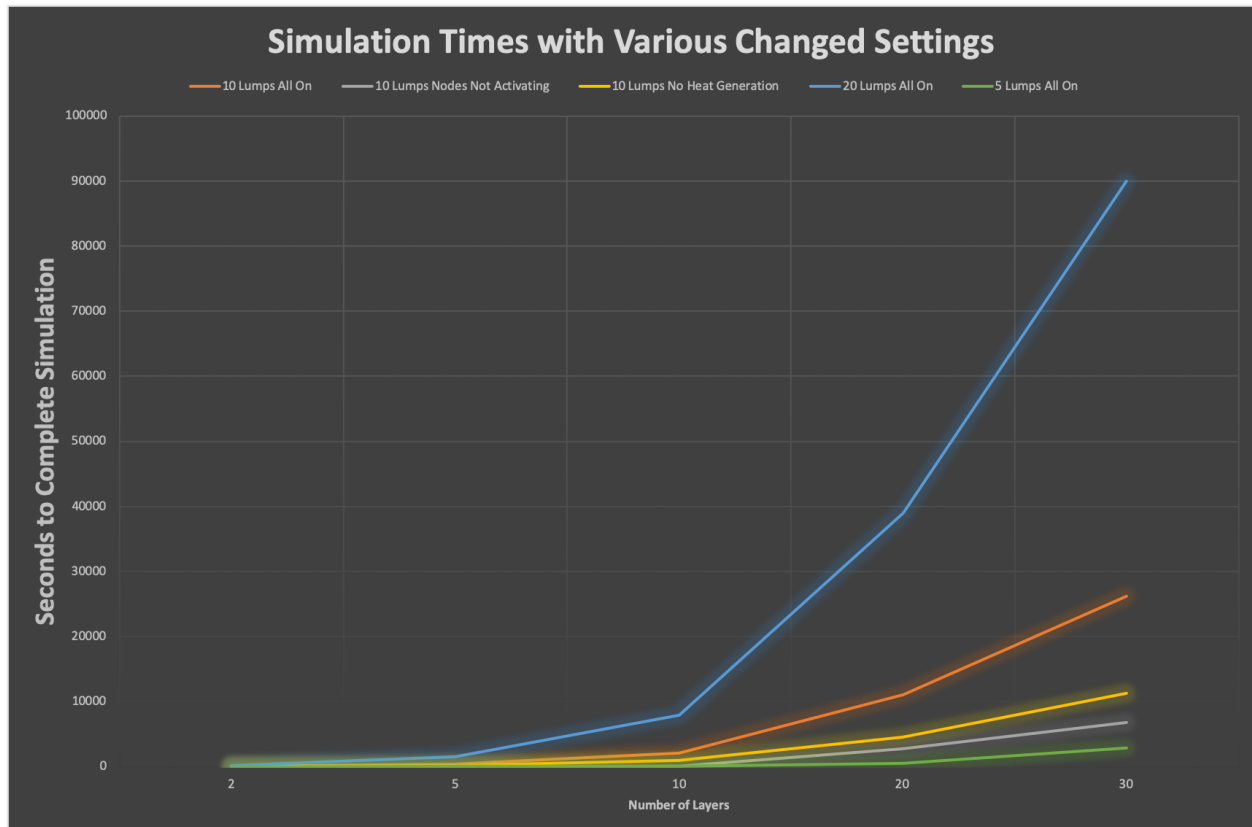


Figure 7.8: Simulation times for different settings enabled and disabled for this analysis. The simulations were timed in MATLAB with their appropriate settings described in the graph.

Chapter 8

Fundamental Contributions and Future Work

It was proposed that this research would make three fundamental contributions:

- Characterizing the effects of NGA methods on the CAD to part process
- Insights into the integration of gravity aligned, non-gravity aligned, and transition zone trajectory planning for WAAM
- Development of a simplified thermal prediction for WAAM for NGA planning

In addition to these contributions, this work also makes the following contributions:

- Development of a path planning application that can plan and integrate GA, NGA, and transition trajectories for WAAM
- Transfer of NGA methods to another WAAM system for use in extending overhang capabilities

The following sections will outline each of these contributions.

8.1 Characterizing the effects of NGA Methods

Multiple representative geometries and features were developed for experimentation on the WAAM cell at the University of Tennessee. Initial experiments validated that modulating

the torch position and orientation with respect to the AM path could be used to help increase a WAAM systems ability to reach near net shape for features with large overhangs. These results were further investigated by developing an experimental test matrix to identify an ideal torch rotation for application on a half cylinder geometry. The results of this work show that while a torch angle perpendicular to the previous layer could reach up to 105° of overhang, that further refining an ideal torch angle without better control of the welding process is not acceptable.

8.2 Insights into Trajectory Planning of complex WAAM features

As a result of having to test NGA methods by modulating torch position and rotation, significant development on a path planning software useful for planning and executing complex NGA trajectories was necessary. Initial stages of this work relied on programming and developing the slices by hand in CAD or Mastercam. After a series of experiments it was found that with proper segmenting and planning that most trajectories could be achieved with proper planning. Initially, simplified approaches to transition zone proved more than effective for building complex geometry segments made up of GA, NGA, and transition segments. However, due to time and software limitations, it was determined that a custom software package was required to help with planning and automation of planning to help test the NGA segments. After development of the software, complex curvilinear shapes that are deposited in three dimensions were easily achievable. The software allows application of the NGA methods to geometry segments to improve overhang near net shape and allows custom and unique path planning solutions for different segment types.

8.3 Development of a Simplified Thermal Prediction

As this tool was meant to help improve path planning, the methodology of the thermal prediction was based in MATLAB. The matlab toolboxes, while helpful proved challenging for getting an accurate and quick simulation, but interfacing with the existing path planning

software framework should be easy given proper calibration and improvement on the speed of the model. The current path planning prediction shows promise as a useful tool for showing hot spots as they relate to path planning and process settings. However, given the limitations of the MATLAB partial differential equation toolbox, the simulations take hours to run for 2D heat transfer settings which is not useful for path planning tools. Future works should consider moving this simulation outside of MATLAB which is not intended for complex heat transfer modeling at high speeds. However, the framework behind the implementation and simplified prediction using node activation seems a promising avenue for future research.

8.4 Path Planning Software and Part Execution

A significant result of this work is the path planning software used to execute and plan parts for the test matrix and complex geometry. The path planning software can take in virtually any slices and execute the segments with the options for very low level control using a position and orientation correction. The software is only limited by the users' understanding of the process settings from the power source with relationship to resultant bead geometry. The software has the capability of planning and executing trajectories for variable height layers, NGA segments, and any other types of geometries that would be desired. A GUI for low level control and visualization was developed to ensure that the path plans can be executed for any trajectory. The software being developed in MATLAB also allows complete customization for future features like kinematic solvers and integration with thermal predictions. The path planning framework is used to develop classes for the data hierarchy, allowing the user to develop algorithms that take macroscopic cues for low level path planning changes.

8.5 Transfer of NGA Methods to another WAAM System

A final significant portion of this work was the transfer of NGA methods to another WAAM system. As mentioned in Chapter 4 and Chapter 6, the torch angle compensation was not fully effective for this work due to the lack of process control on the cell at the

University of Tennessee. However the Lincoln Electric mBAAM system at the Manufacturing Demonstration Facility (MDF) has real time control processes which keep the WAAM process stable, and a known layer height and width. Previously, the MDF reported 20° of overhang without NGA methodology for overhangs. The NGA methods were applied to a notional tool mold to increase the capabilities of overhangs up to 35 degrees, while being able to meet near net shape. The part was built without a part positioner and was still able to complete complex curvilinear geometry and be machined to form.

8.6 Future Research

The use of NGA methods is a very broad field with many applications. While WAAM was the focus of the research presented here, the NGA methods have applications in all other types of AM. Any DED process with a deposition end effector which can be rotated can use these principles to help reach near net shape. The NGA methods being applied to systems with different materials will also prove a challenge with different material properties. There needs to be significant research into the full effectiveness of these methods for different processes settings, but the initial transfer of NGA methods to another WAAM system shows that these techniques can be adaptable.

A large missing element for this work is real time control and/or bead modeling to predict near net shape of the resultant layer. At this point, the layer height and width for the contours were based on previous experience and experimental measurements. Better process control to ensure bead height and width proved very helpful for implementing NGA methods on the MDF Lincoln Electric system, and with further process control it stands to be reasoned that the NGA methods could be adapted for most AM processes. Process control on the UTK system would also help eliminate the sources of error on the experimental test matrix resulting from imprecise wire feed and other process issues. Another similar option is to develop a bead model tied to process settings. Predicting accurately the bead shape and behavior would greatly improve the ability to reach near net shape, particularly for overhang features where gravity effects are significant.

Another major aspect of future research is further development on thermal modeling. While the theory behind node activation for WAAM proves promising, MATLAB and its existing partial differential equation toolbox requires significant processing power and is not well suited to solve the highly complex 3D heat transfer problem given by WAAM, even with the significant simplifications presented in this work. Given that the effectiveness of NGA methods relies on keeping the surface tension of the weld pool strong enough to weld out of position, a high accuracy thermal model which could predict the success of a trajectory would be an invaluable tool for path planning. A validation tool that could accurately ensure that the chosen path planning would result in meltdown would provide a significant time and money saver. However, given the rapid prototyping nature of AM, it is also desirable to balance accuracy with having to wait hours for a simulation of temperature.

The last aspect of future research is tied to the path planning software developed for this work. The path planning software was designed to provide researchers a faster and more customized solution to planning part segments with torch rotation and shift. The capabilities of this software are limited to generating trajectories given from existing slices. The slicing is still done manually through commercial technologies given that the slicing distance are dictated by heuristic bead height and width. Integrating slicing capabilities into the path planner would allow further custom solutions involving NGA methods. Secondly, the path planner does not have any understanding of the robotic system associated with deposition. During development of the path planner, significant debugging and simplifications were made to exportation of the trajectories to ensure that the robot did not experience kinematic errors like joint limits and singularities. Tying in the kinematics of the robot to path planning is the next step to ensuring that path planning for complex NGA trajectories can be achieved.

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Appendices

A Single Wall Overhang Results

A.1 35° Single Wall Overhang

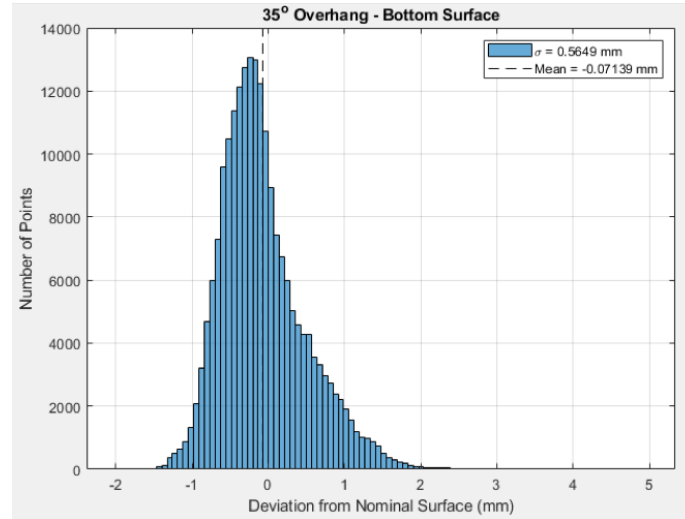


Figure 1: Graph of the bottom surface Deviation for the metrology comparison.

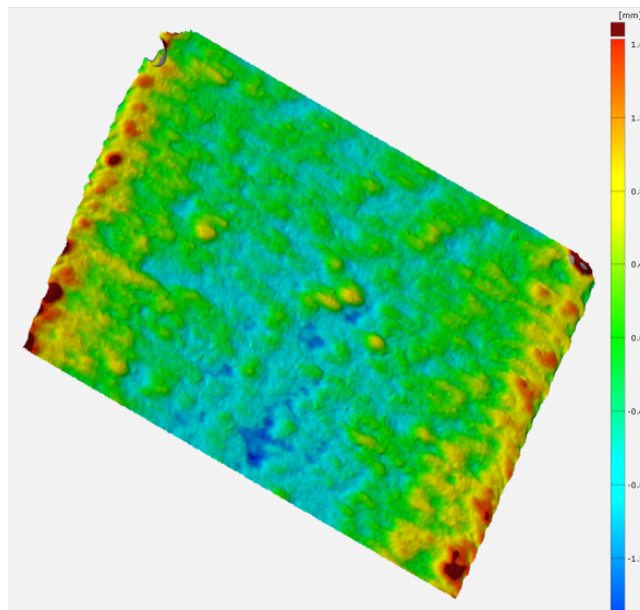


Figure 2: A picture of the scanned bottom surface with deviation map.

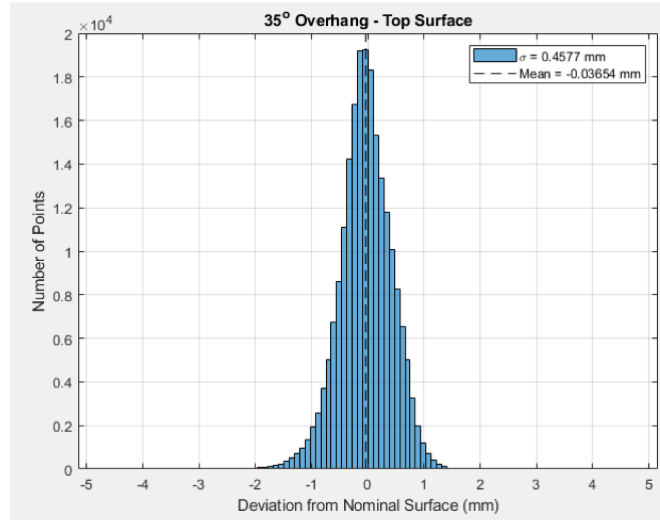


Figure 3: Graph of the top surface Deviation for the metrology comparison.

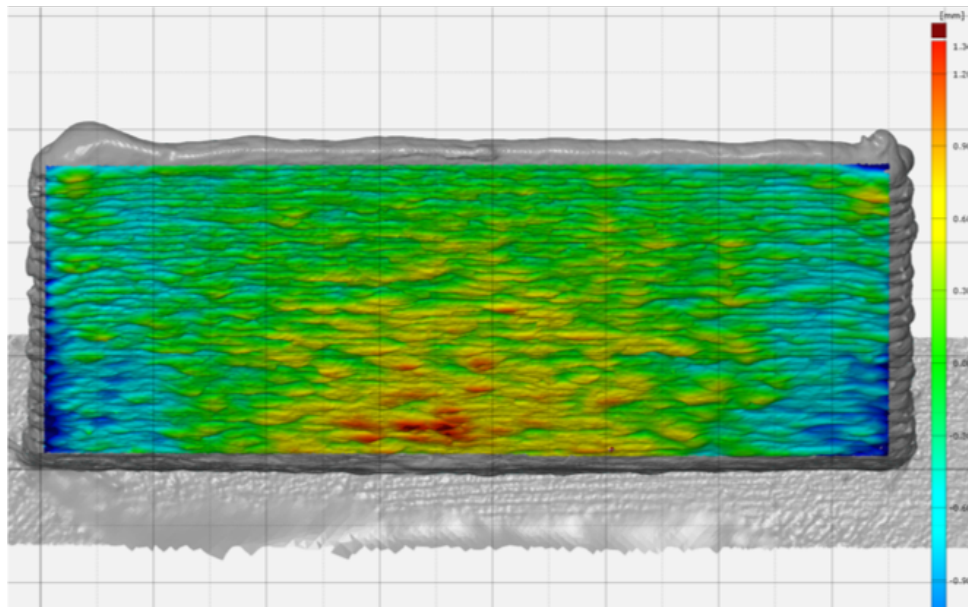


Figure 4: A picture of the scanned top surface with deviation map.

A.2 45° Single Wall Overhang

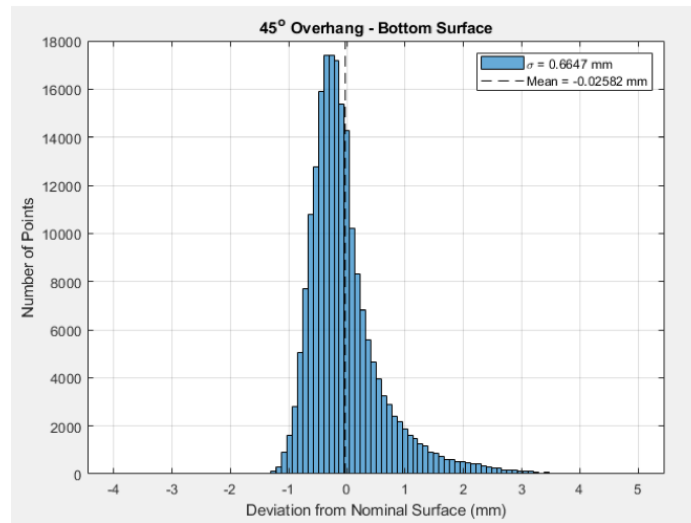


Figure 5: Graph of the bottom surface Deviation for the metrology comparison.

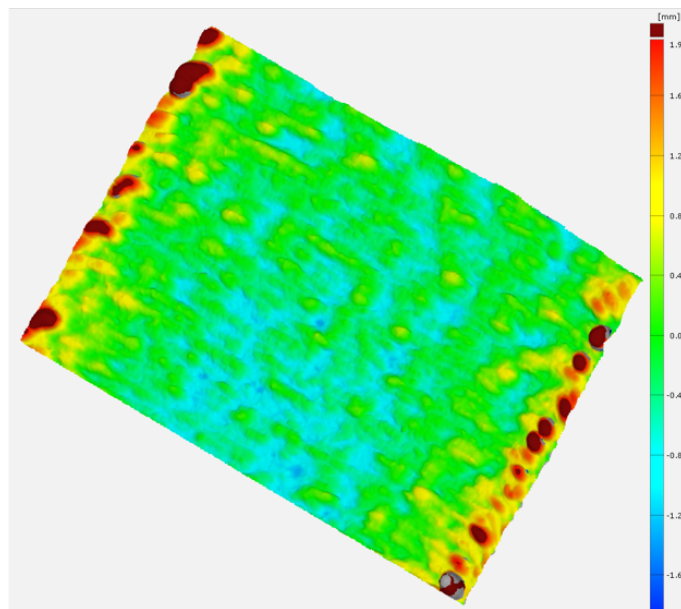


Figure 6: A picture of the scanned bottom surface with deviation map.

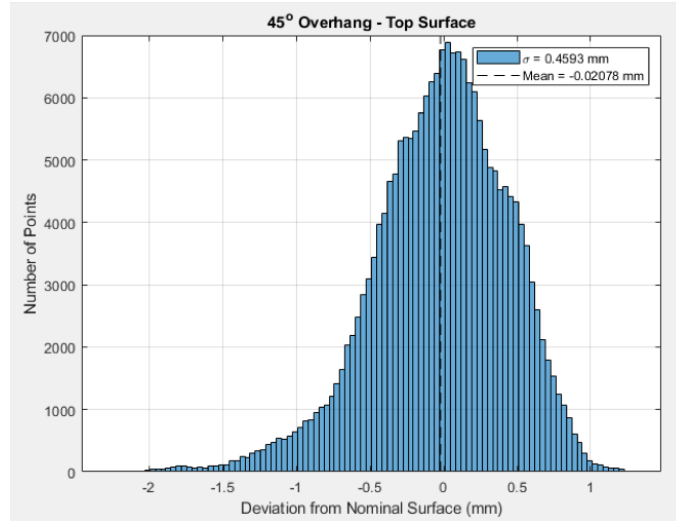


Figure 7: Graph of the top surface Deviation for the metrology comparison.

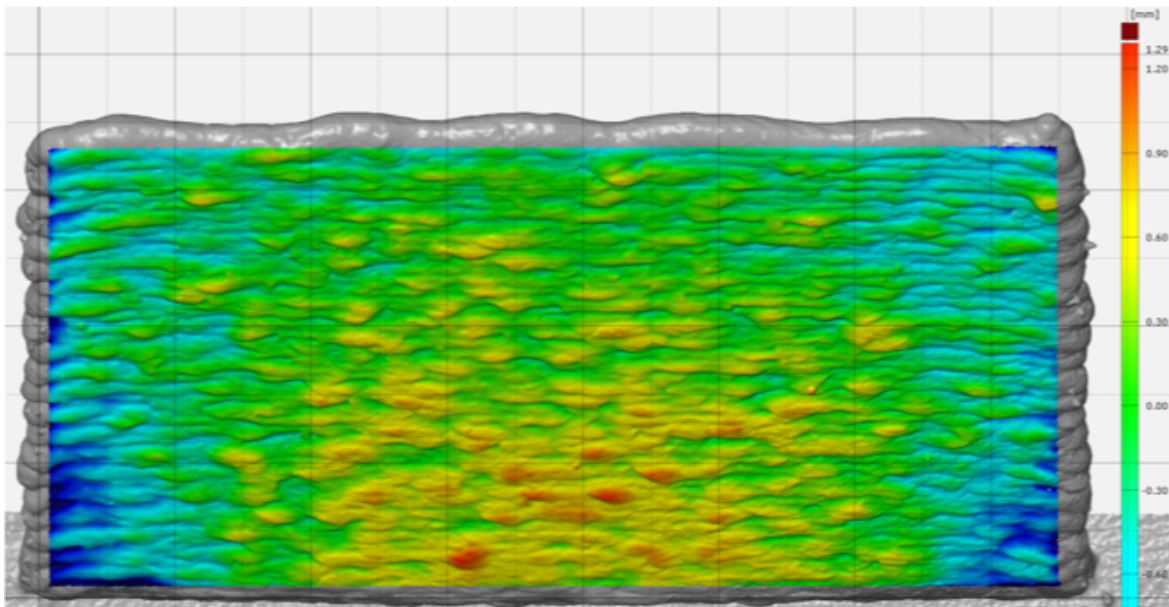


Figure 8: A picture of the scanned top surface with deviation map.

A.3 55° Single Wall Overhang

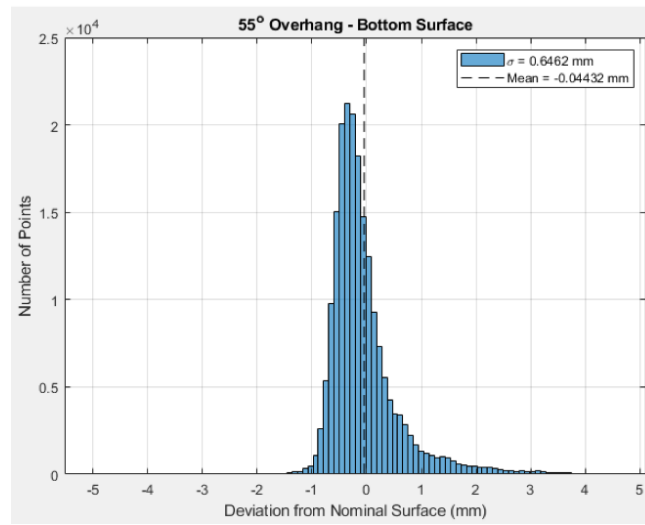


Figure 9: Graph of the bottom surface Deviation for the metrology comparison.

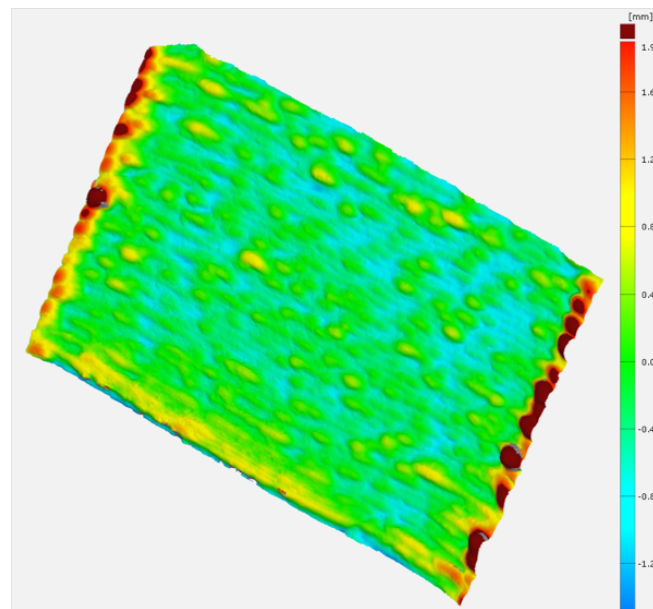


Figure 10: A picture of the scanned bottom surface with deviation map.

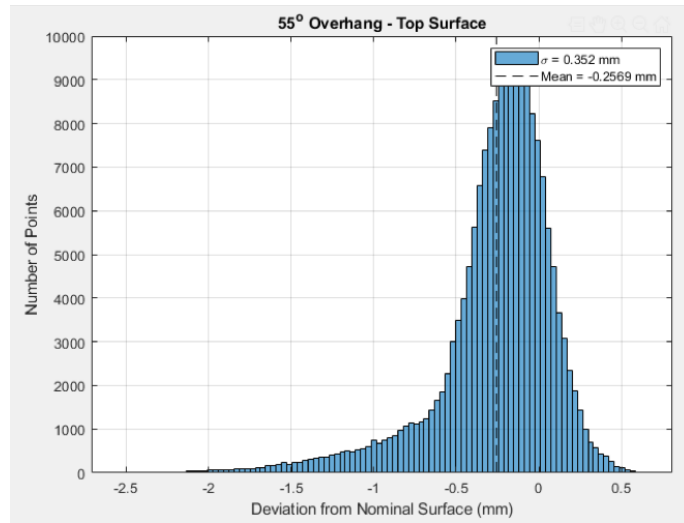


Figure 11: Graph of the top surface Deviation for the metrology comparison.

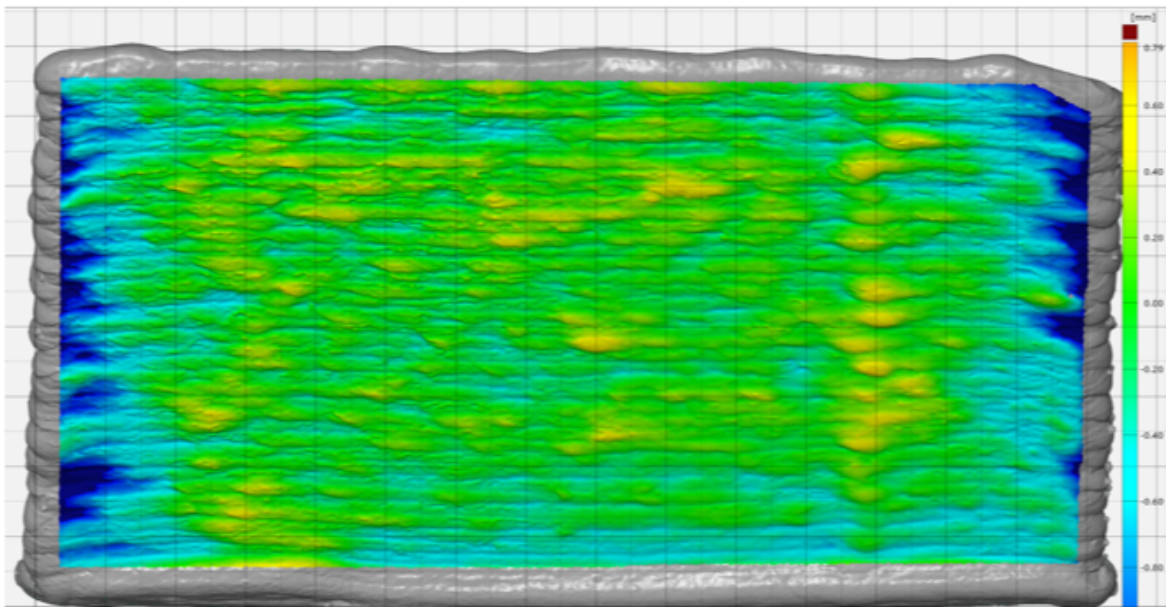


Figure 12: A picture of the scanned top surface with deviation map.

A.4 65° Single Wall Overhang

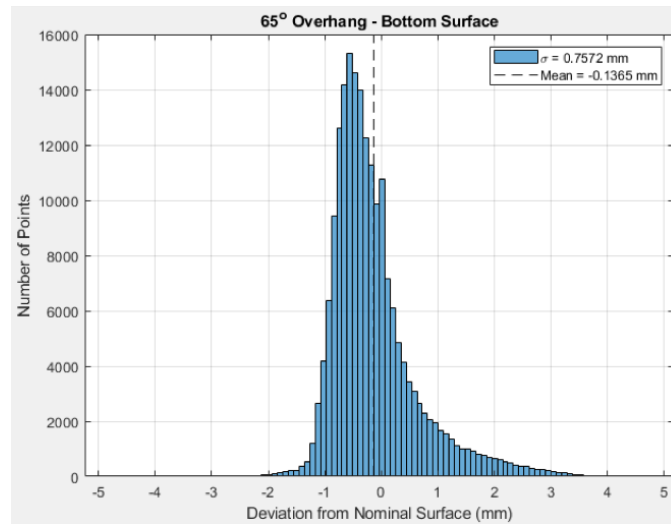


Figure 13: Graph of the bottom surface Deviation for the metrology comparison.

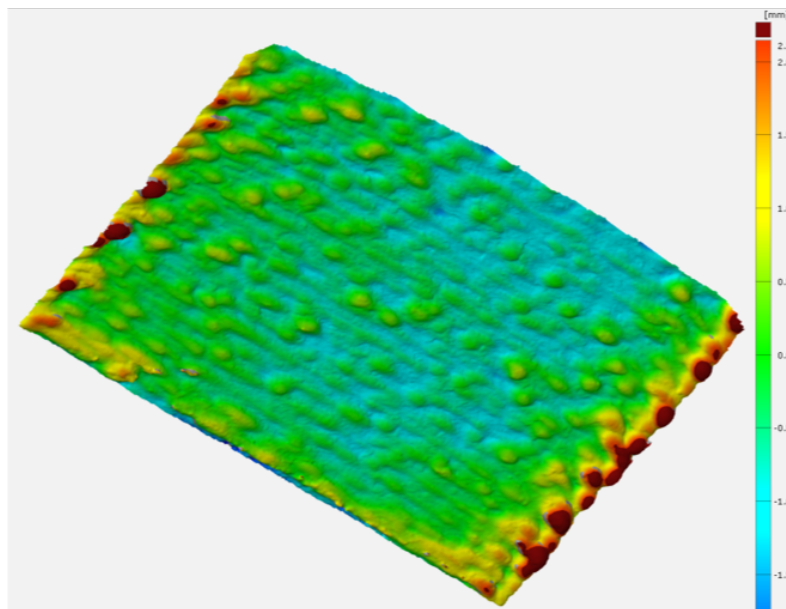


Figure 14: A picture of the scanned bottom surface with deviation map.

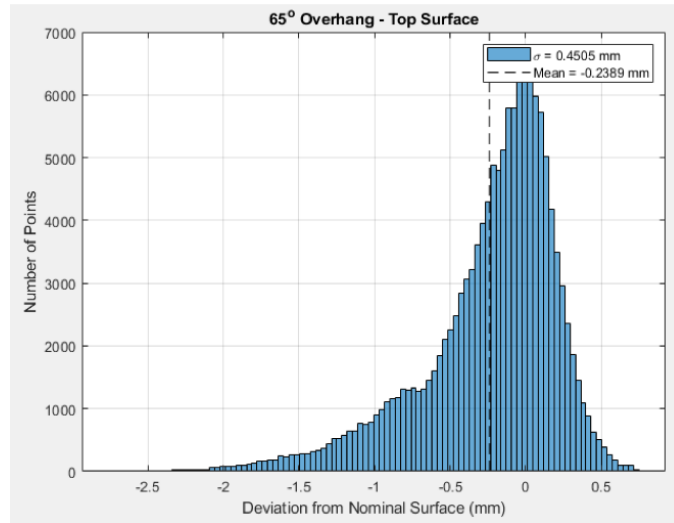


Figure 15: Graph of the top surface Deviation for the metrology comparison.

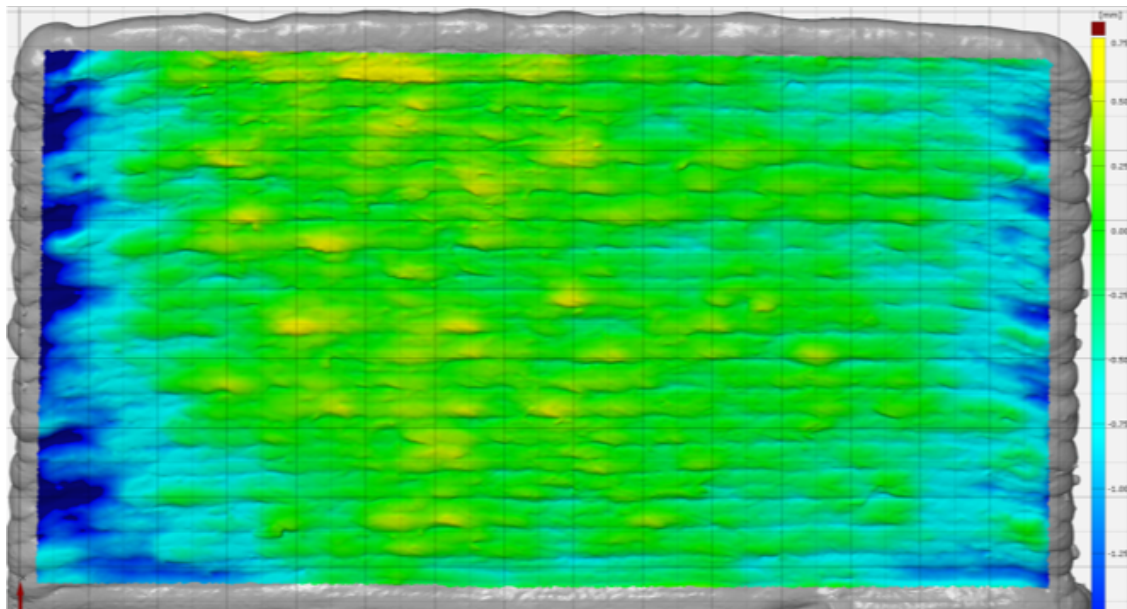


Figure 16: A picture of the scanned top surface with deviation map.

A.5 75° Single Wall Overhang

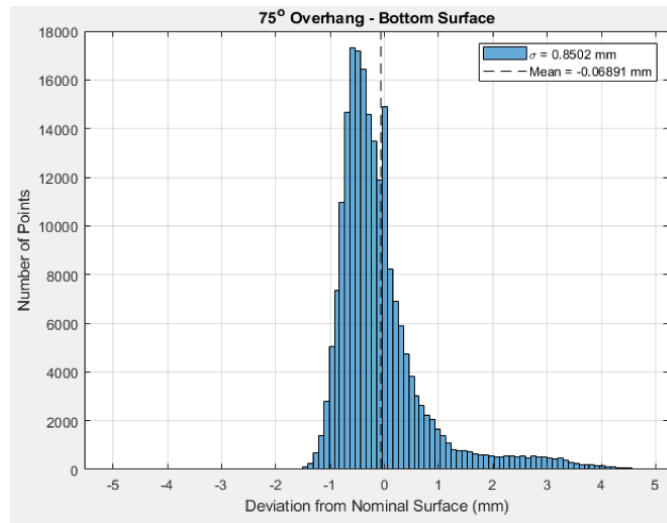


Figure 17: Graph of the bottom surface Deviation for the metrology comparison.

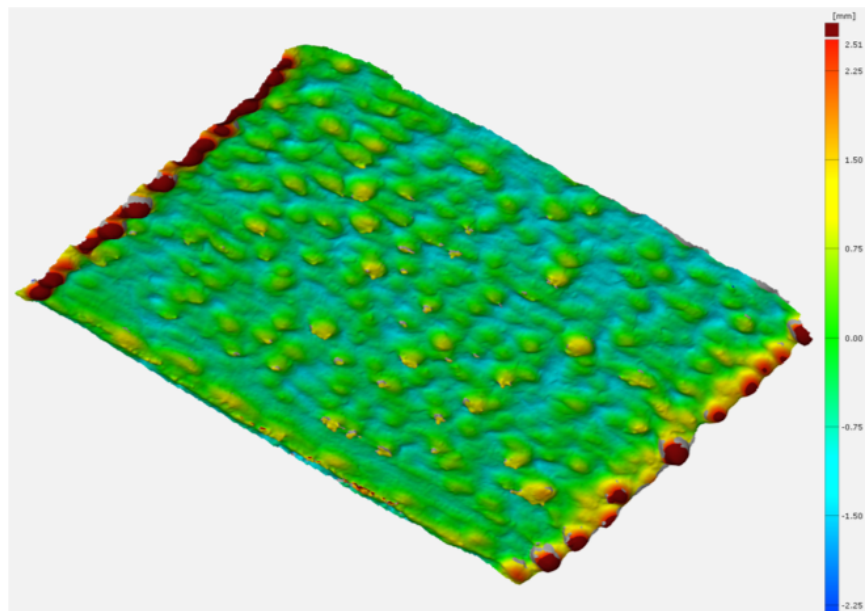


Figure 18: A picture of the scanned bottom surface with deviation map.

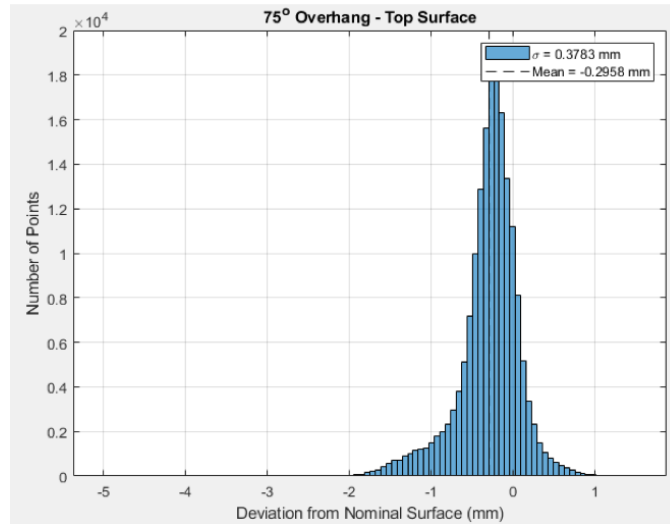


Figure 19: Graph of the top surface Deviation for the metrology comparison.

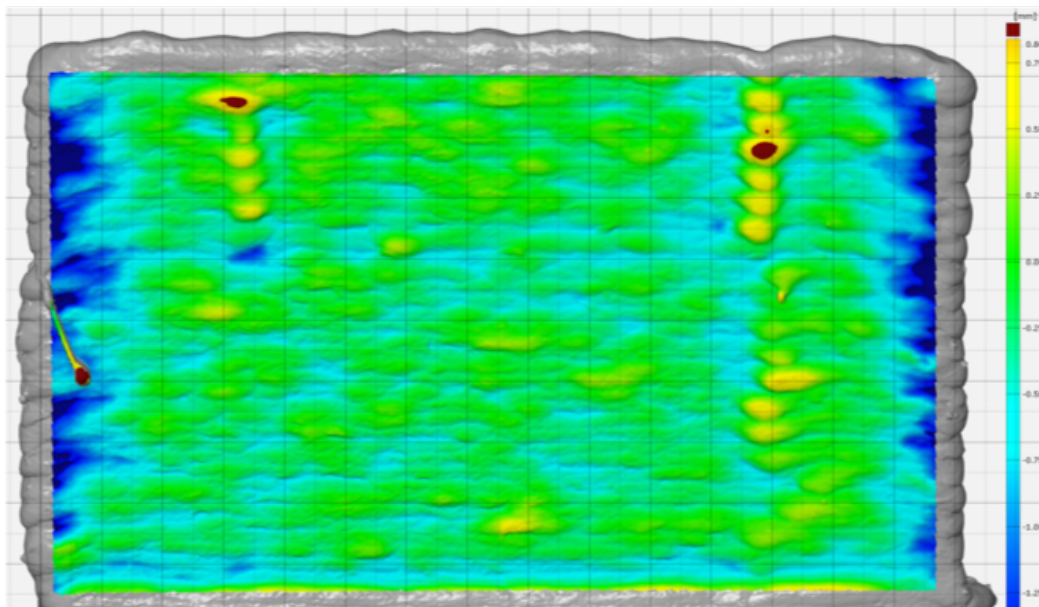


Figure 20: A picture of the scanned top surface with deviation map.

A.6 85° Single Wall Overhang

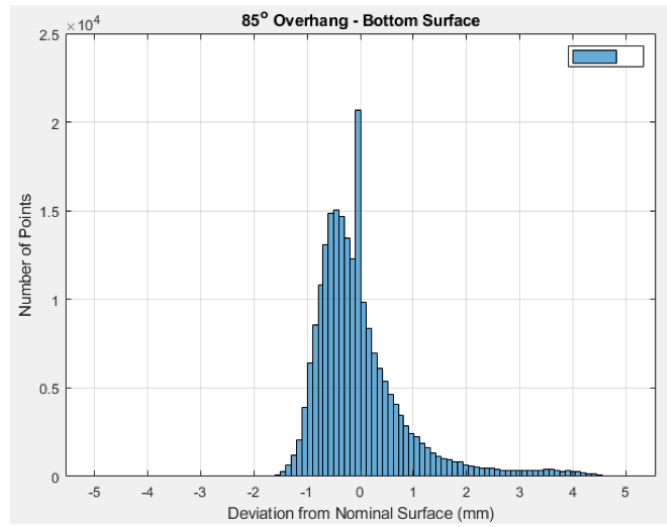


Figure 21: Graph of the bottom surface Deviation for the metrology comparison.

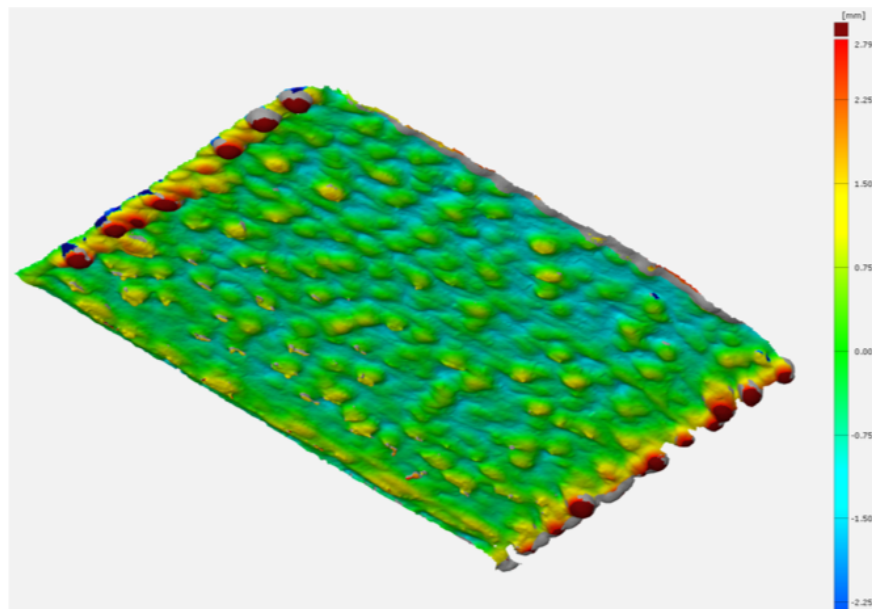


Figure 22: A picture of the scanned bottom surface with deviation map.

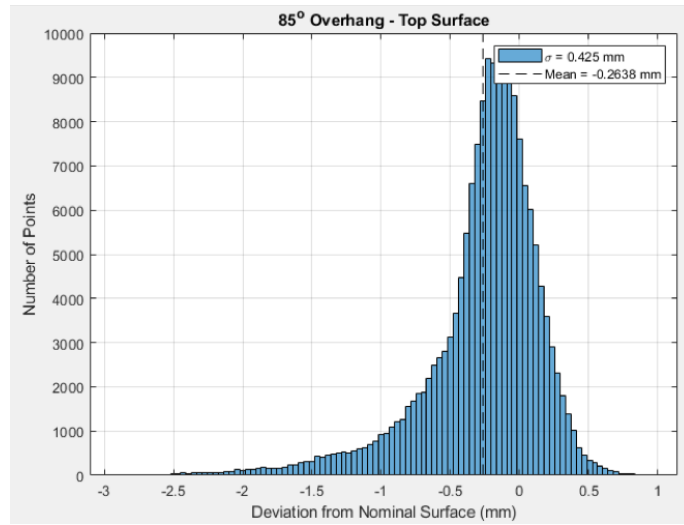


Figure 23: Graph of the top surface Deviation for the metrology comparison.

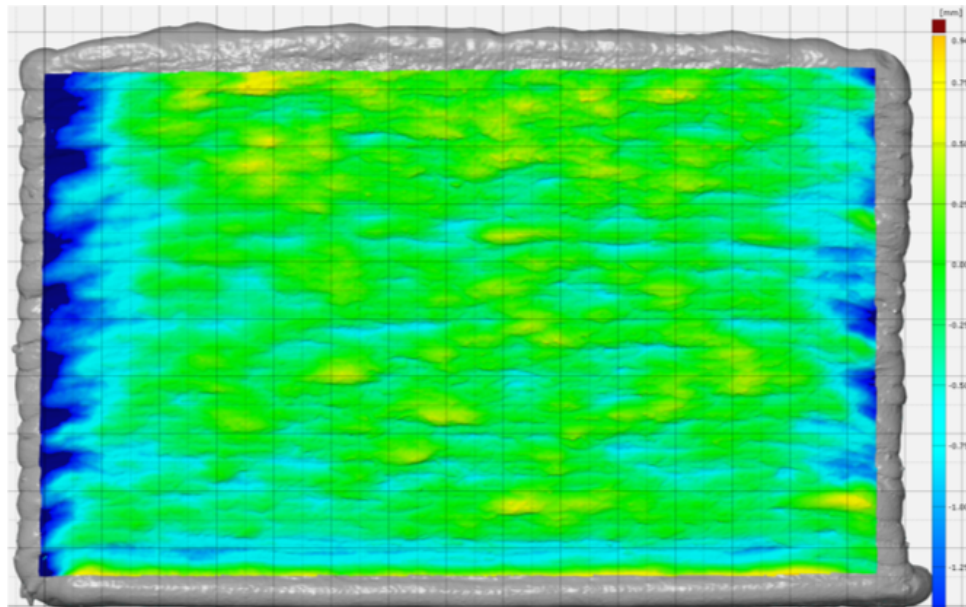


Figure 24: A picture of the scanned top surface with deviation map.

A.7 95° Single Wall Overhang

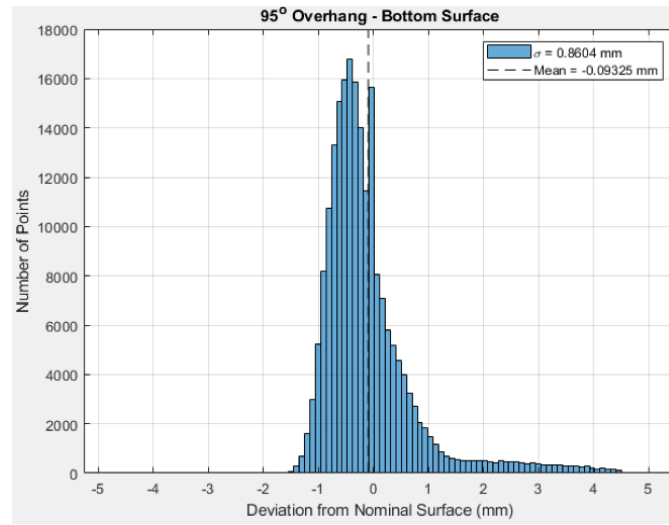


Figure 25: Graph of the bottom surface Deviation for the metrology comparison.

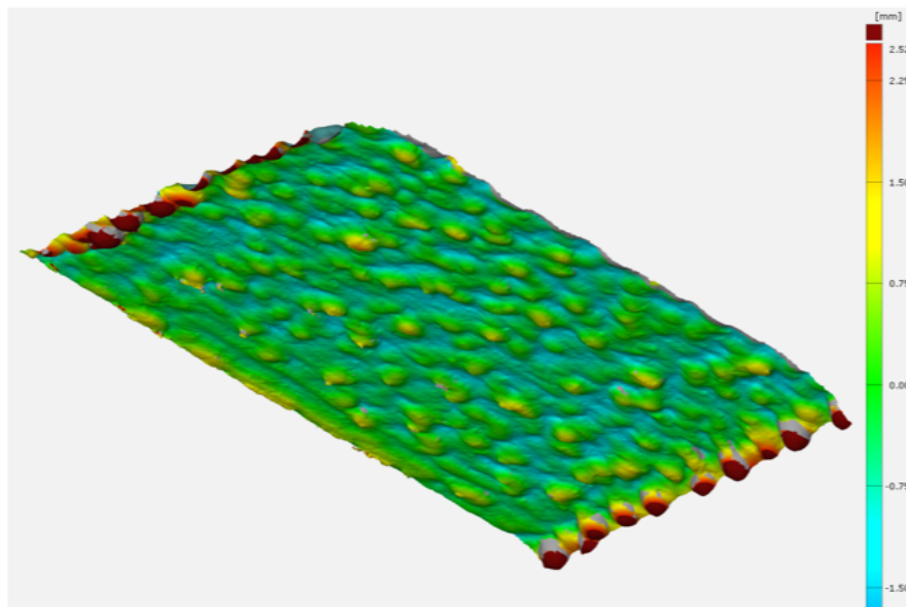


Figure 26: A picture of the scanned bottom surface with deviation map.

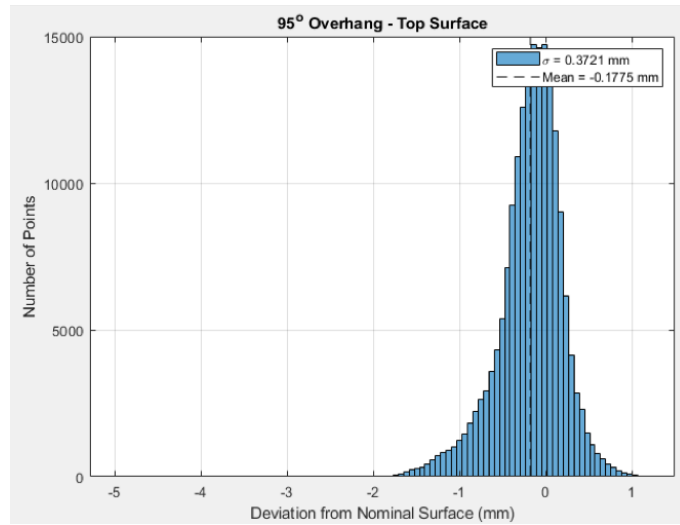


Figure 27: Graph of the top surface Deviation for the metrology comparison.

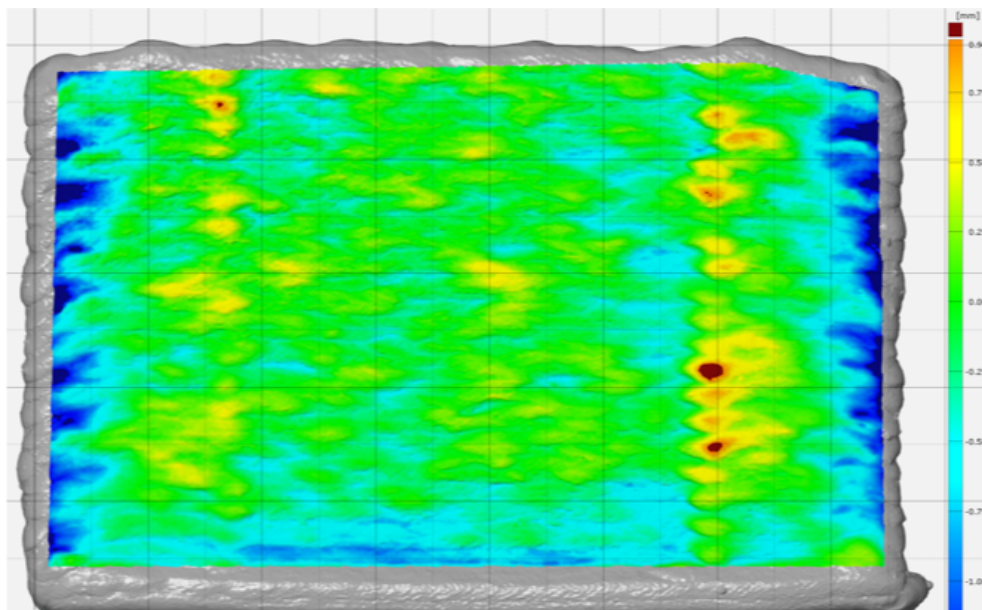


Figure 28: A picture of the scanned top surface with deviation map.

A.8 105° Single Wall Overhang

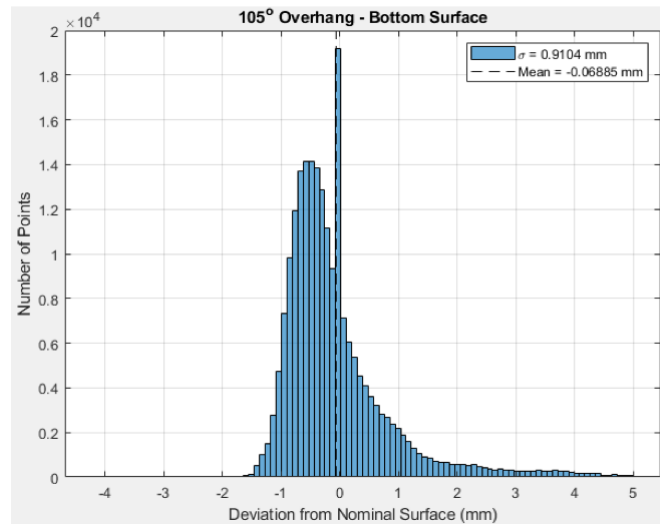


Figure 29: Graph of the bottom surface Deviation for the metrology comparison.

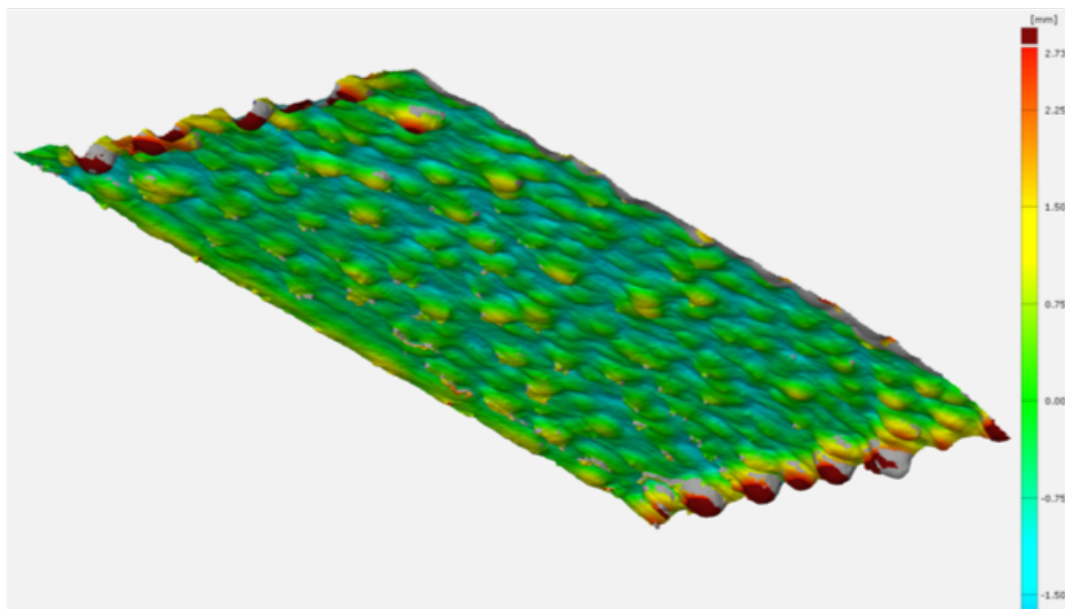


Figure 30: A picture of the scanned bottom surface with deviation map.

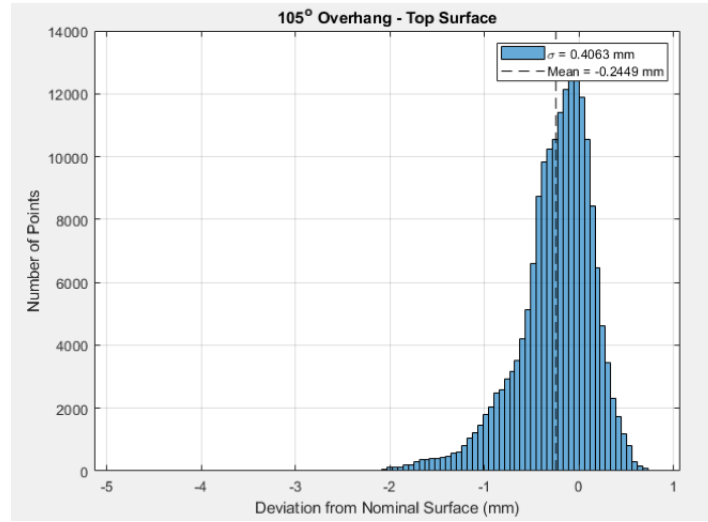


Figure 31: Graph of the top surface Deviation for the metrology comparison.

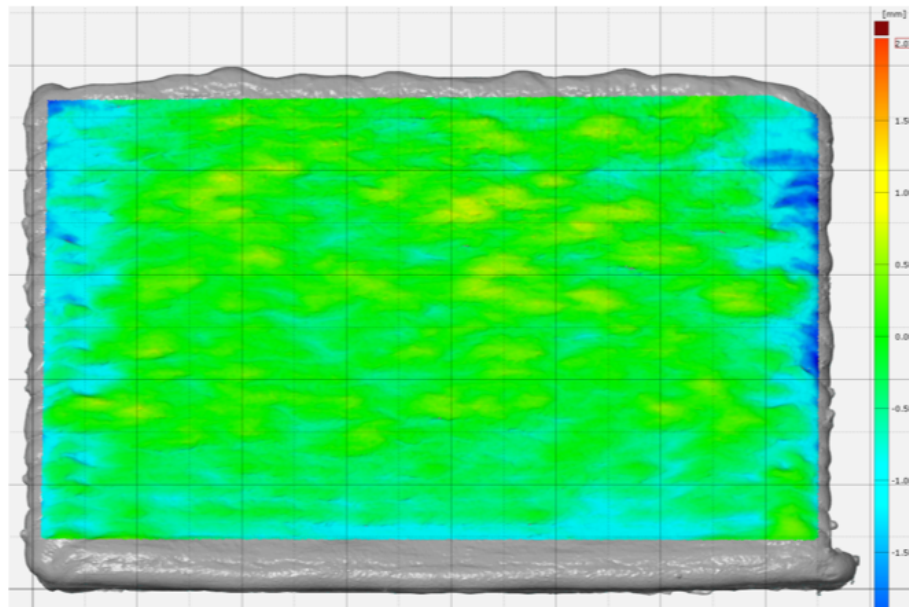


Figure 32: A picture of the scanned top surface with deviation map.

B Final Test Matrix Results

B.1 45 Degree Base Alignment and Graphs

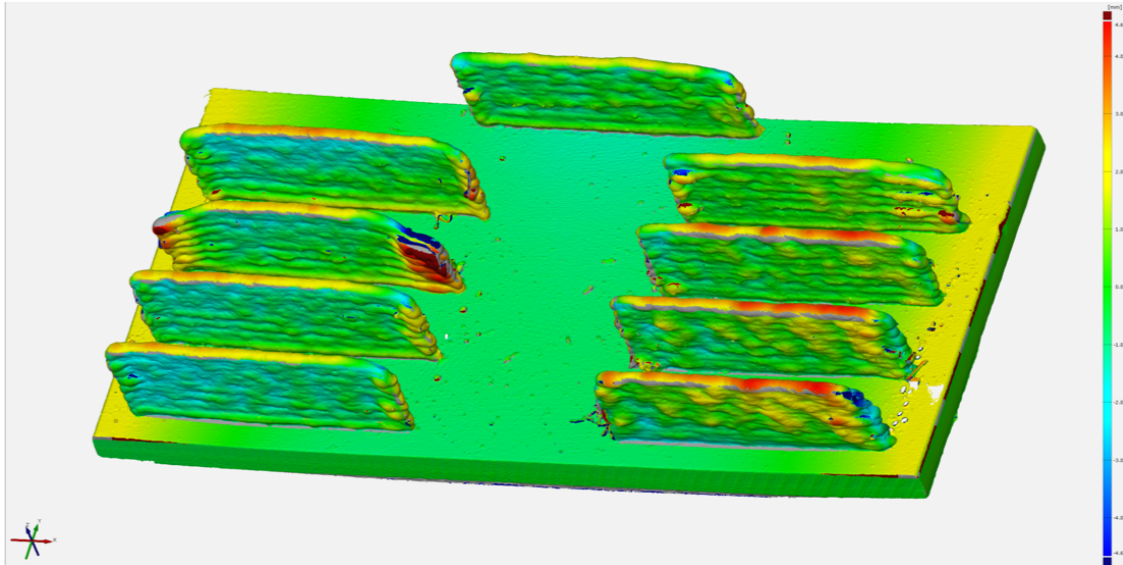


Figure 33: Isometric view of the geometry.

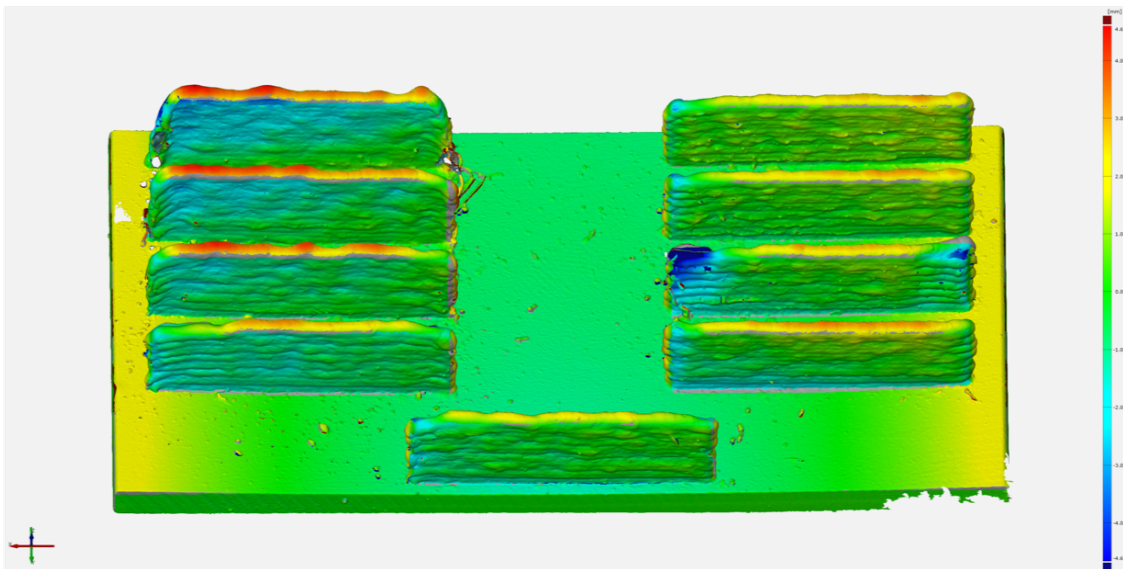


Figure 34: Top view of the geometry.

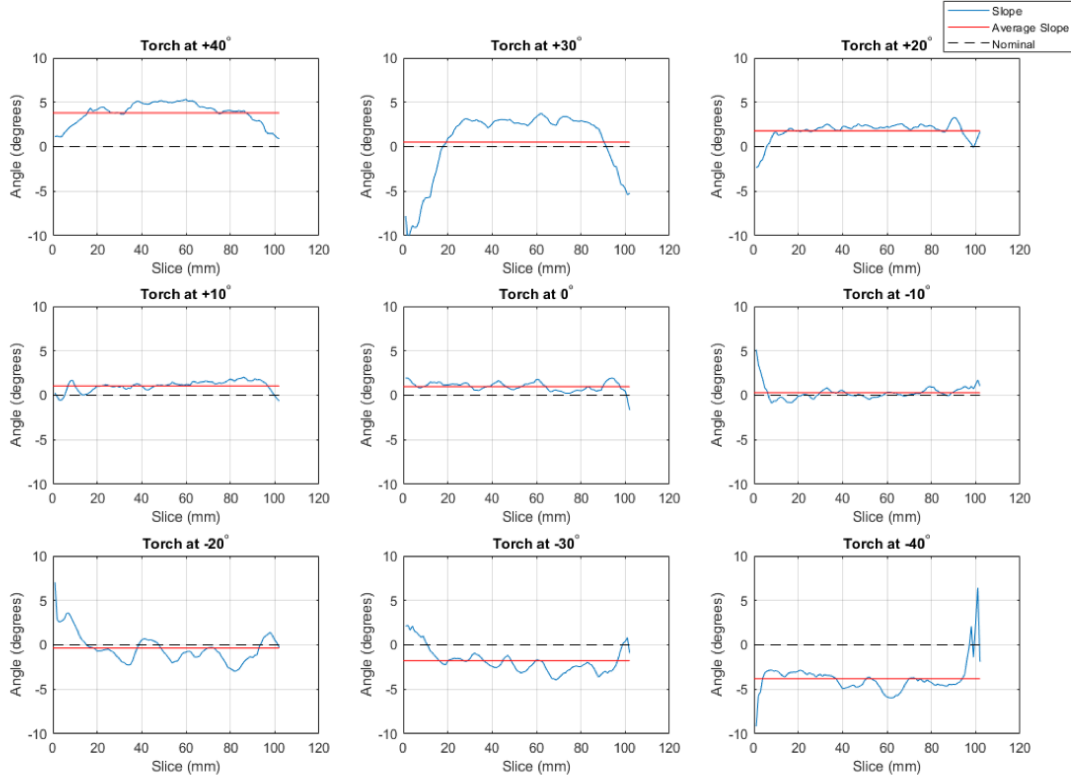


Figure 35: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

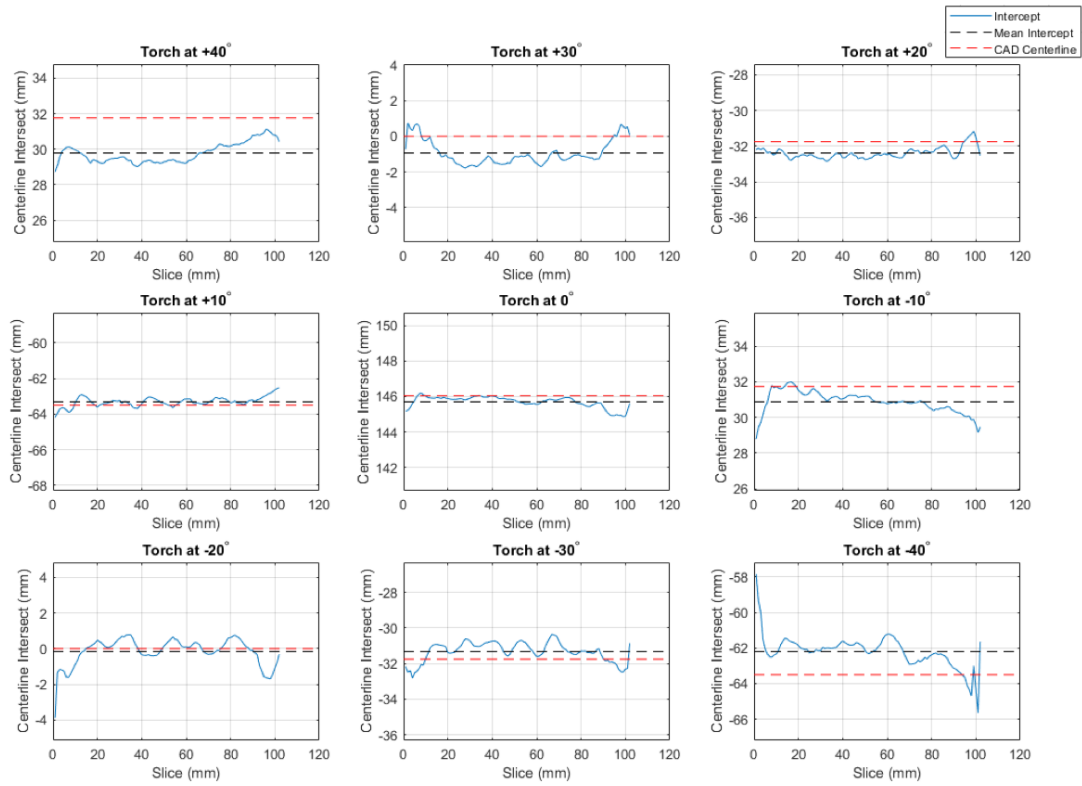


Figure 36: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

B.2 65 Degree Base Alignment and Graphs

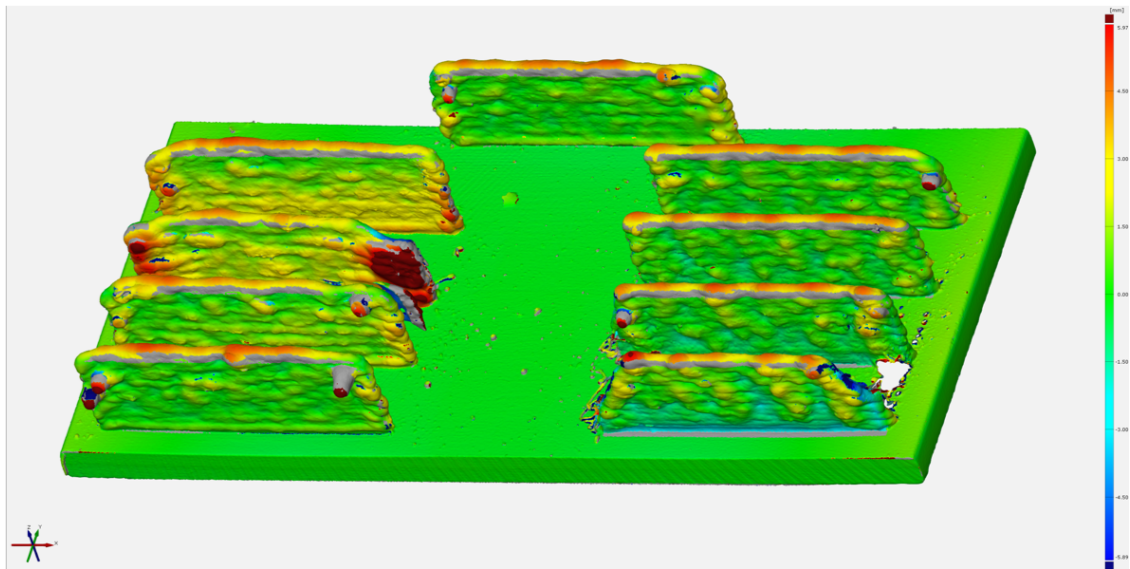


Figure 37: Isometric view of the geometry.

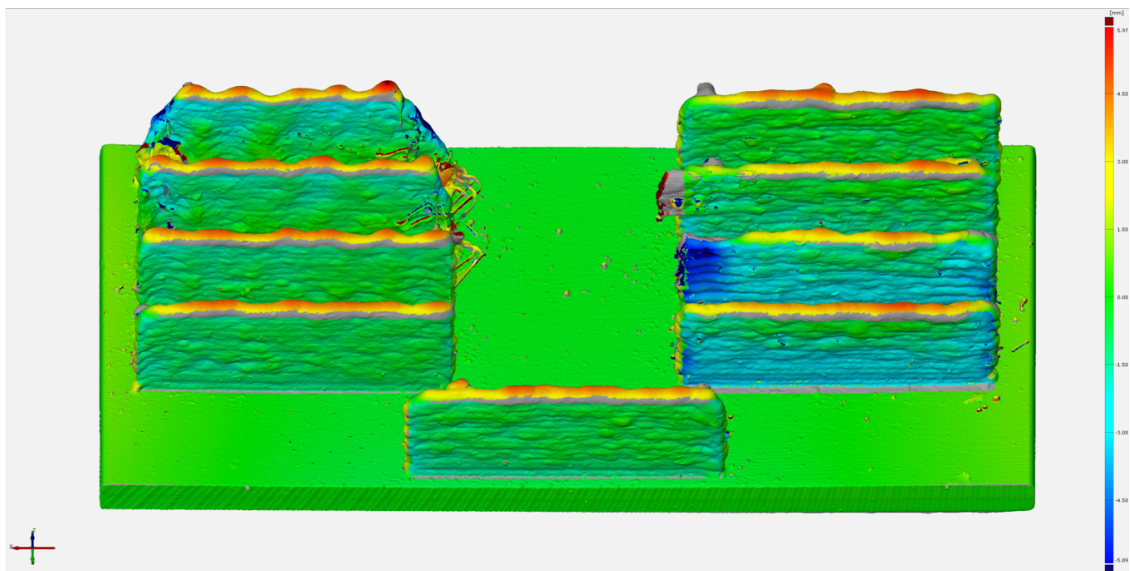


Figure 38: Top view of the geometry.

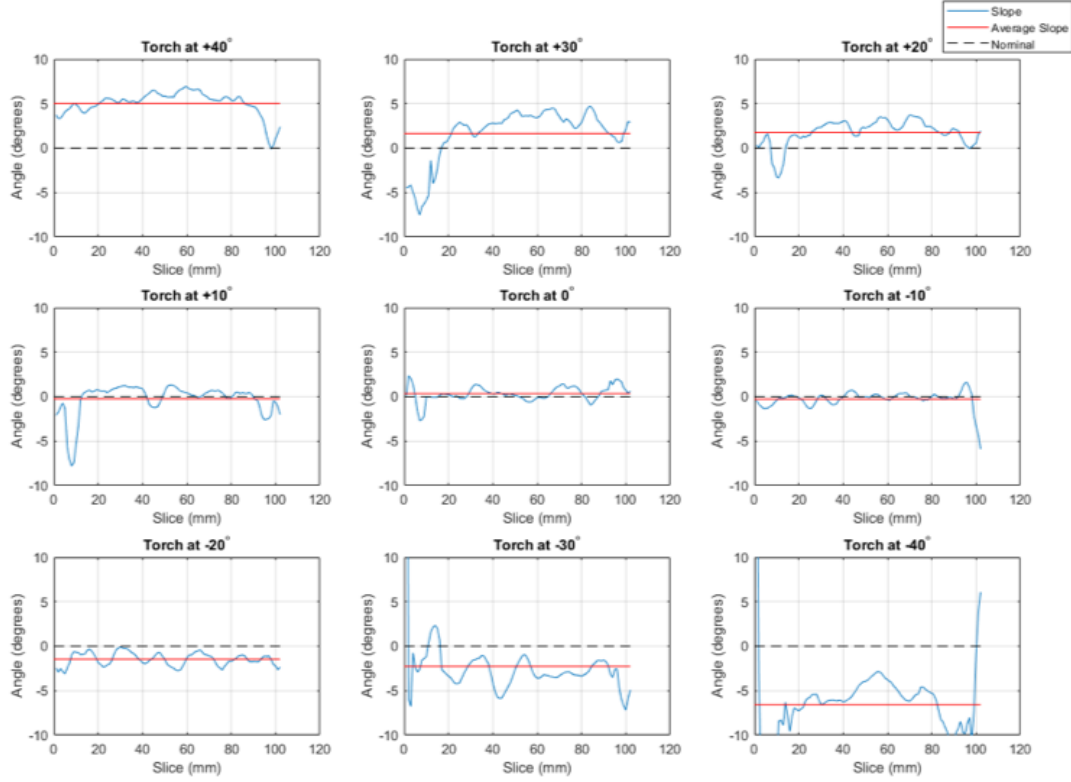


Figure 39: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

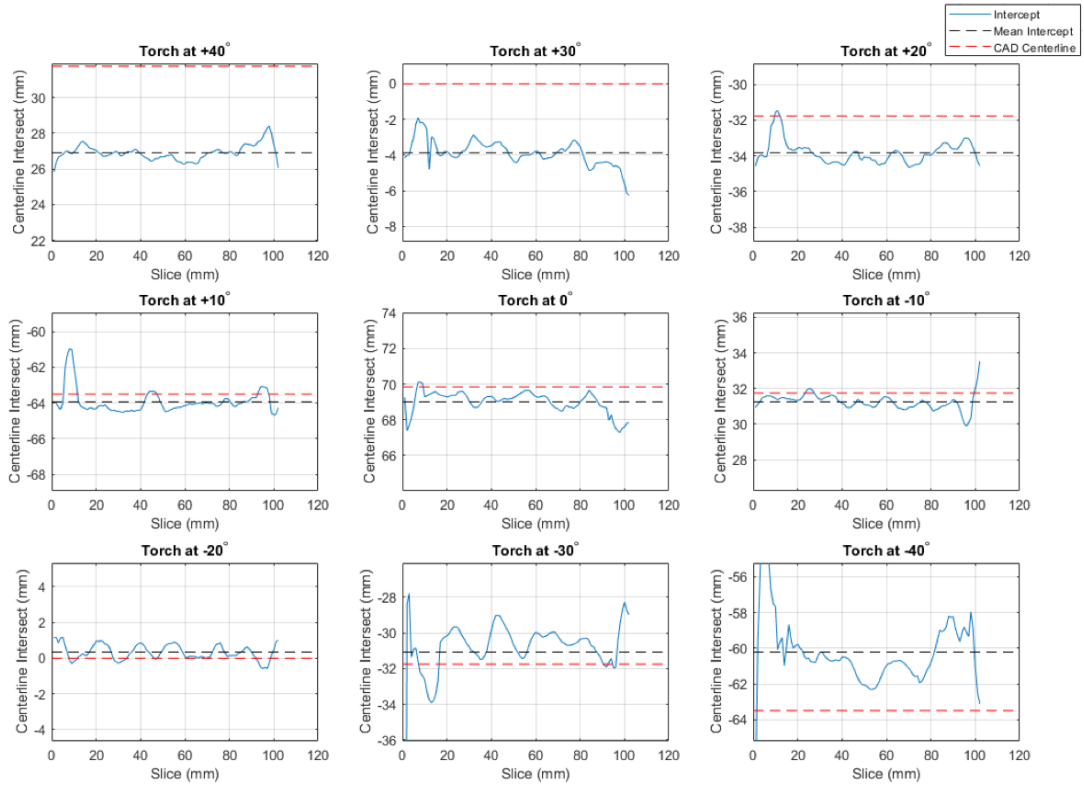


Figure 40: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

B.3 90 Degree Base Alignment and Graphs

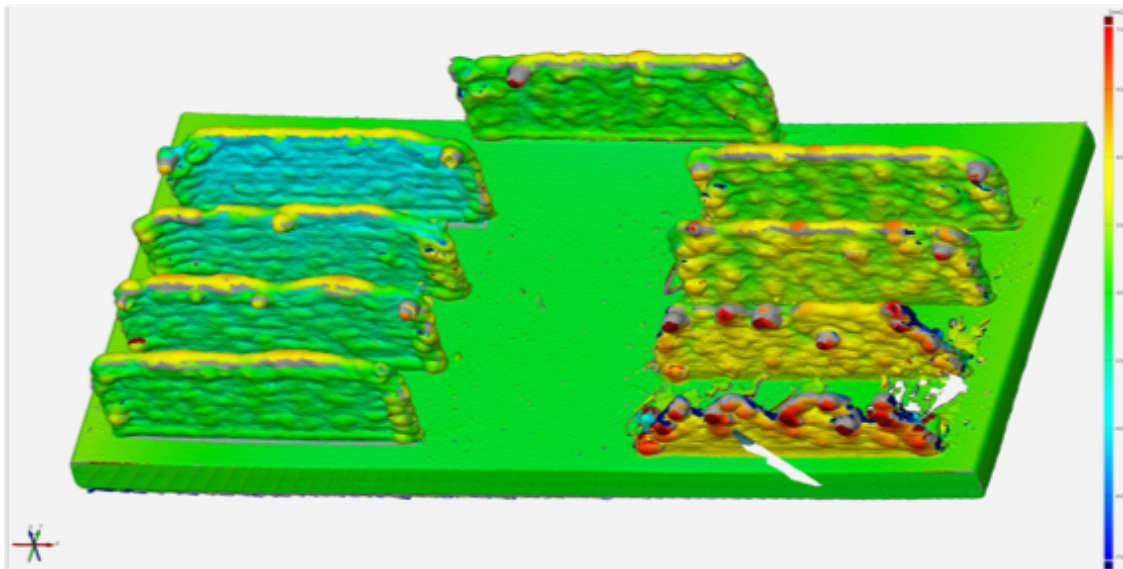


Figure 41: Isometric view of the geometry.

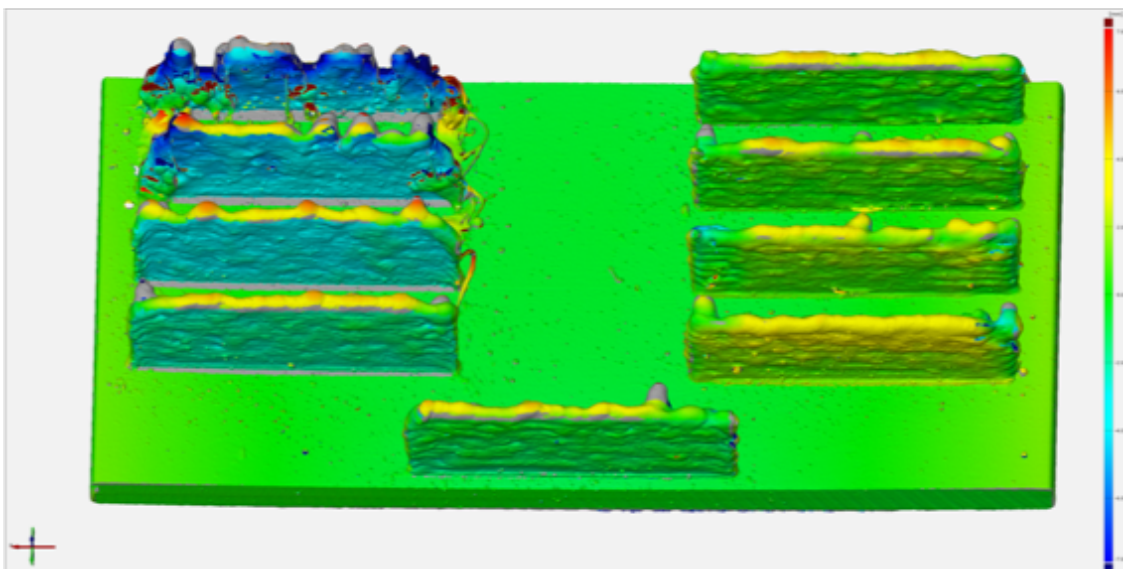


Figure 42: Top view of the geometry.

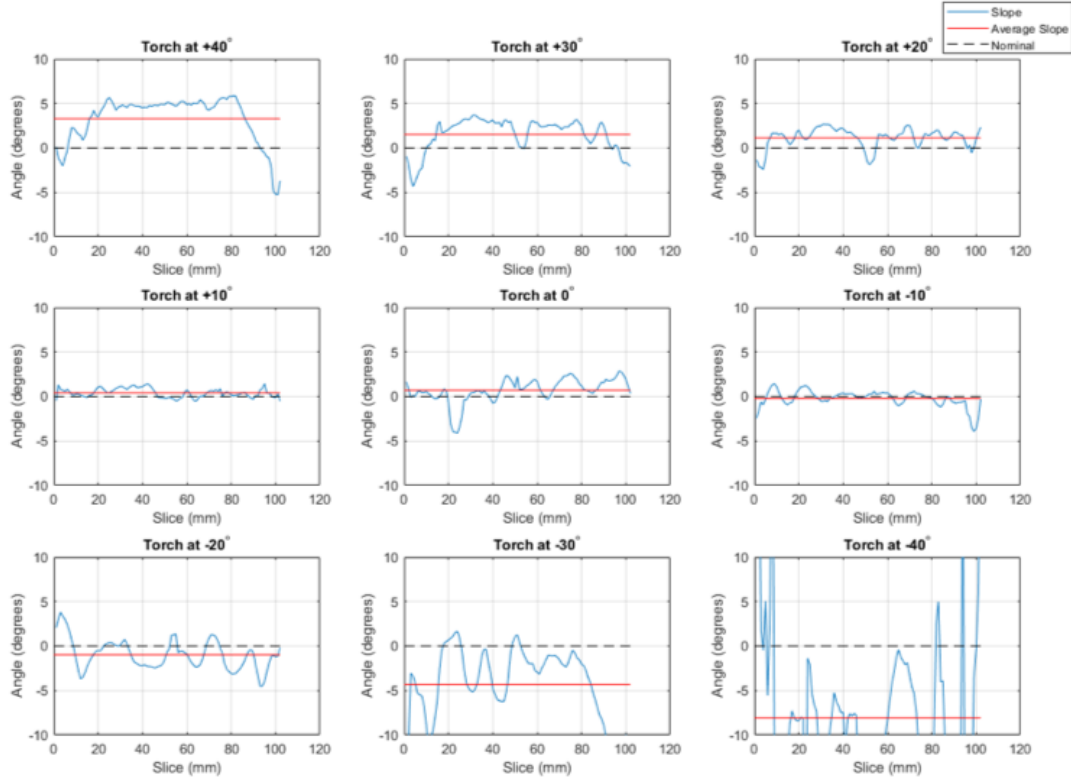


Figure 43: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

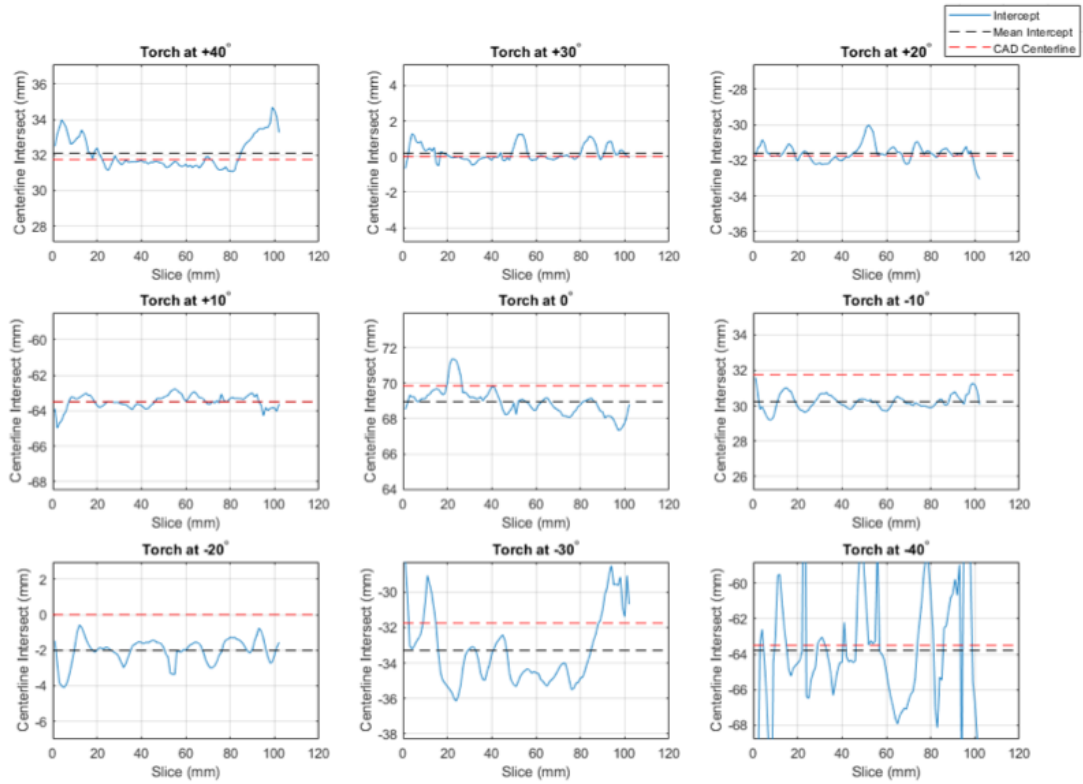


Figure 44: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

B.4 45 Degree Shifted Alignment and Graphs

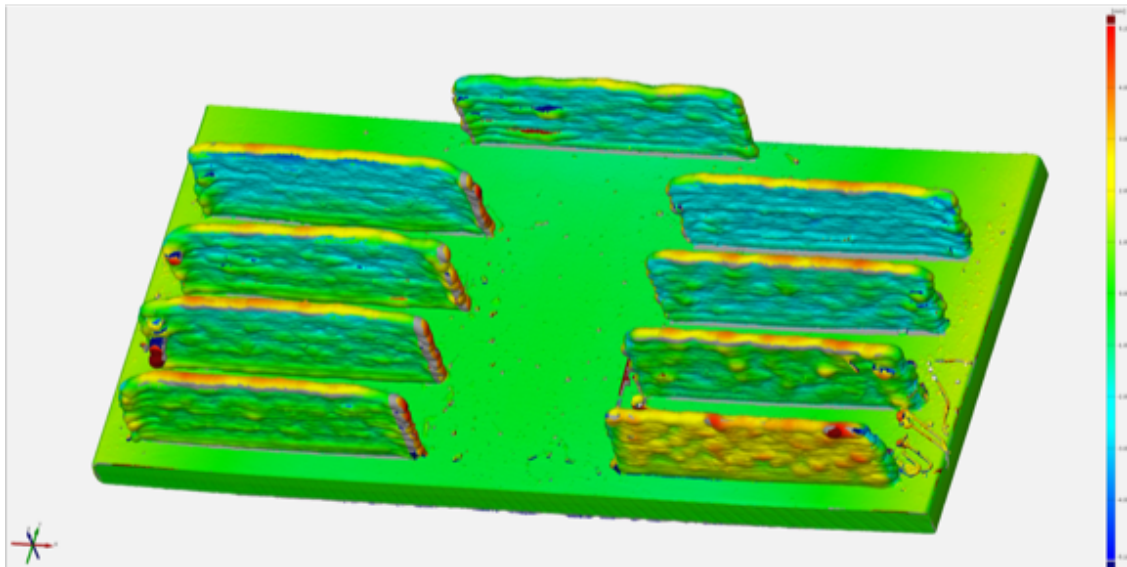


Figure 45: Isometric view of the geometry.

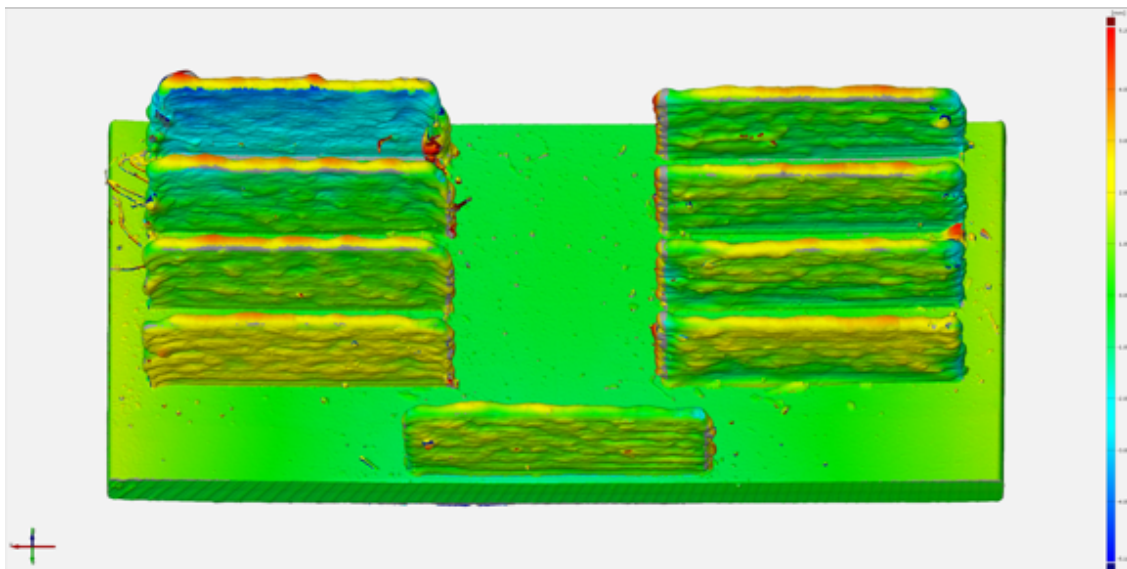


Figure 46: Top view of the geometry.

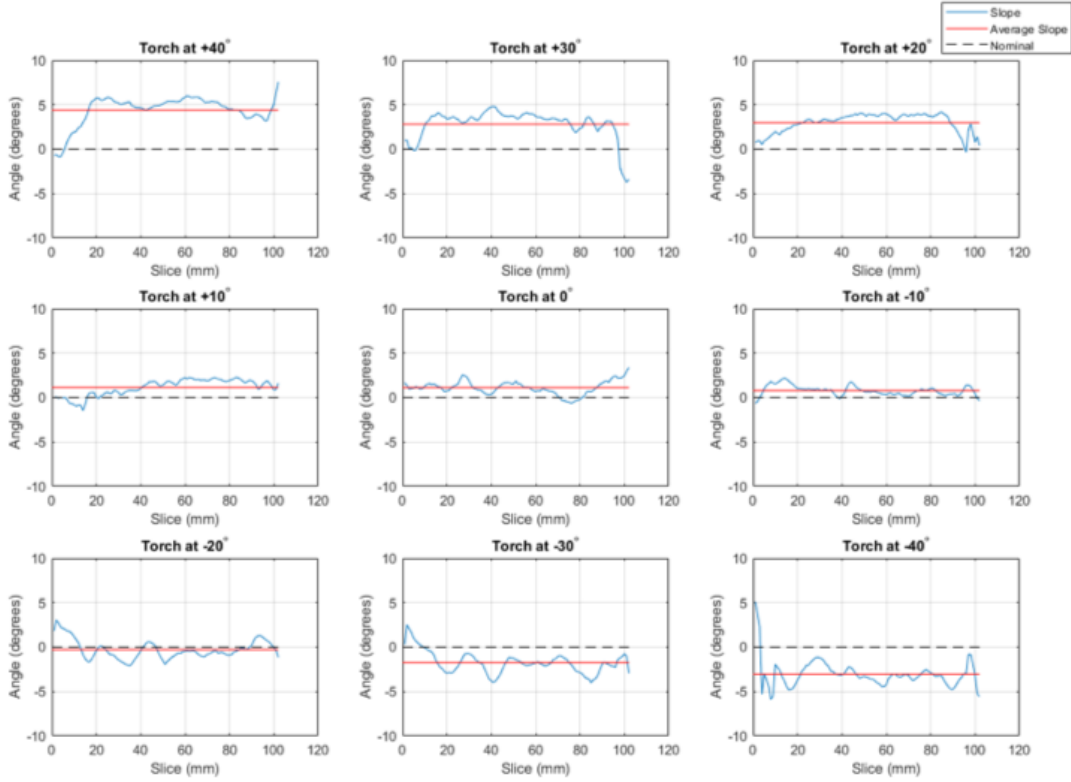


Figure 47: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

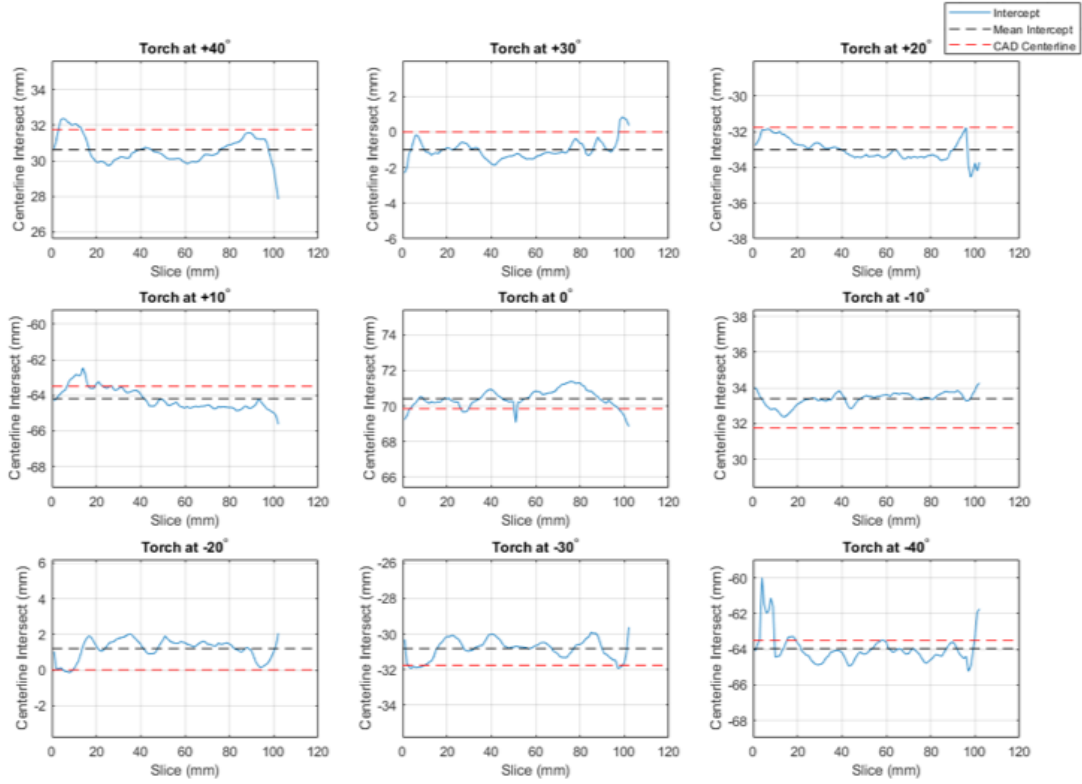


Figure 48: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

B.5 65 Degree Shifted Alignment and Graphs

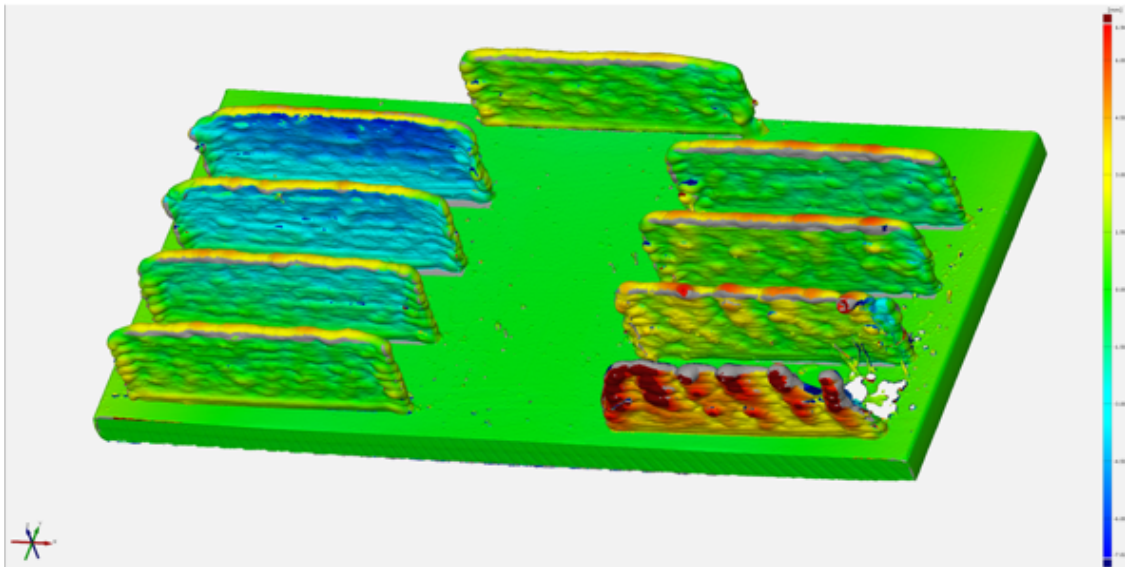


Figure 49: Isometric view of the geometry.

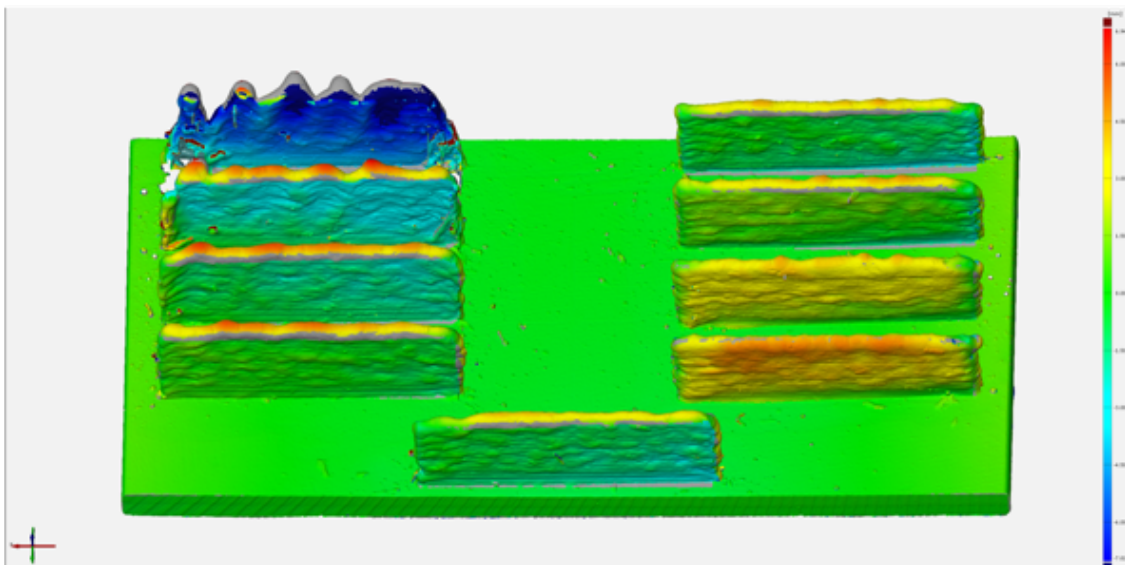


Figure 50: Top view of the geometry.

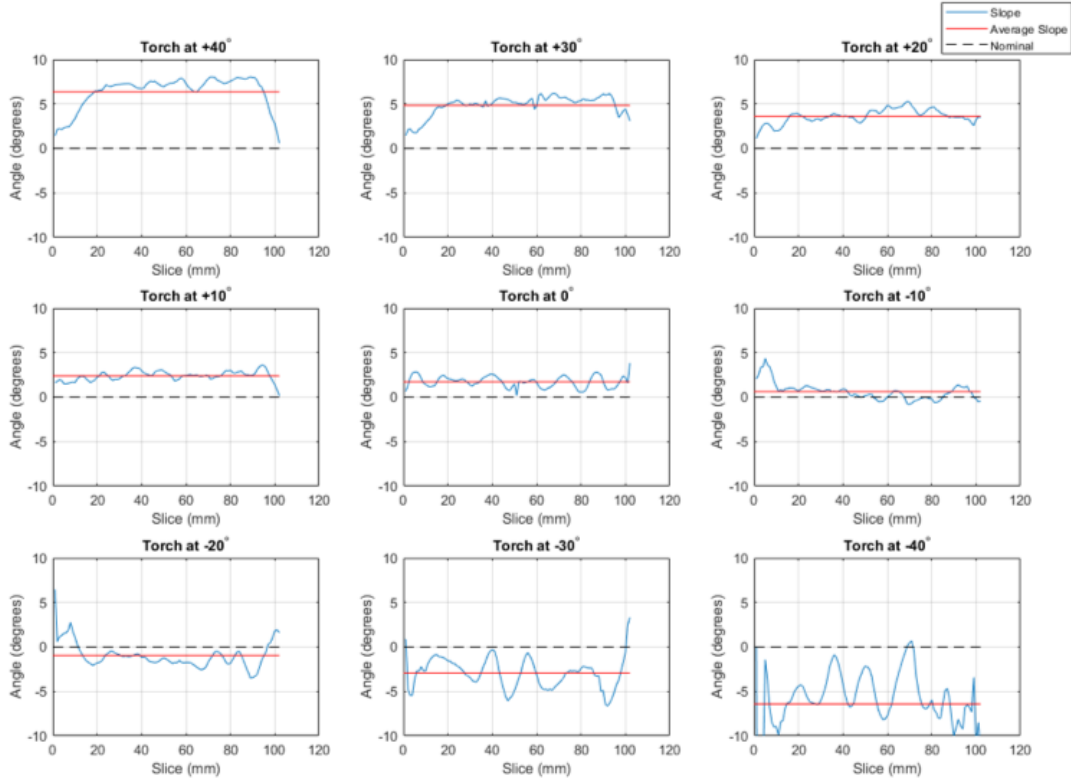


Figure 51: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

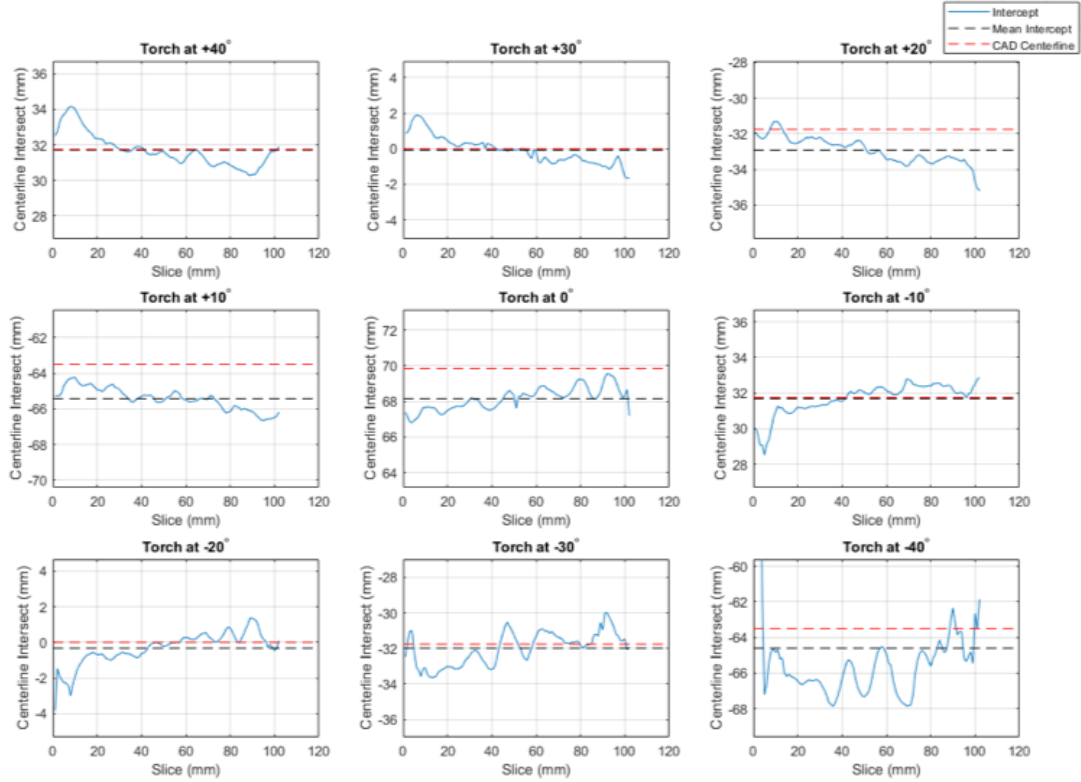


Figure 52: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

B.6 90 Degree Shifted Alignment and Graphs

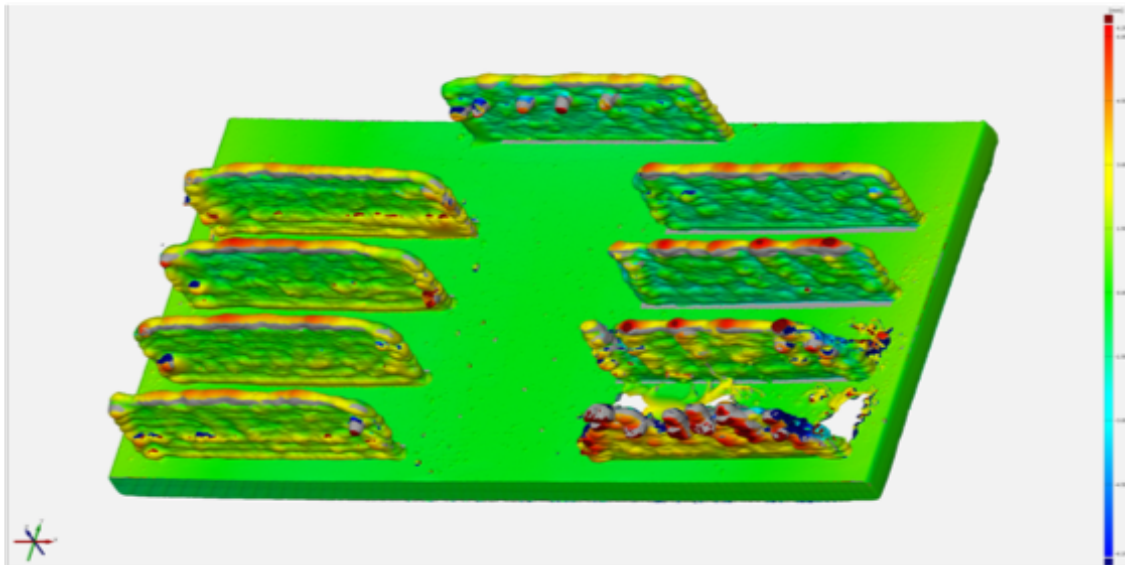


Figure 53: Isometric view of the geometry.

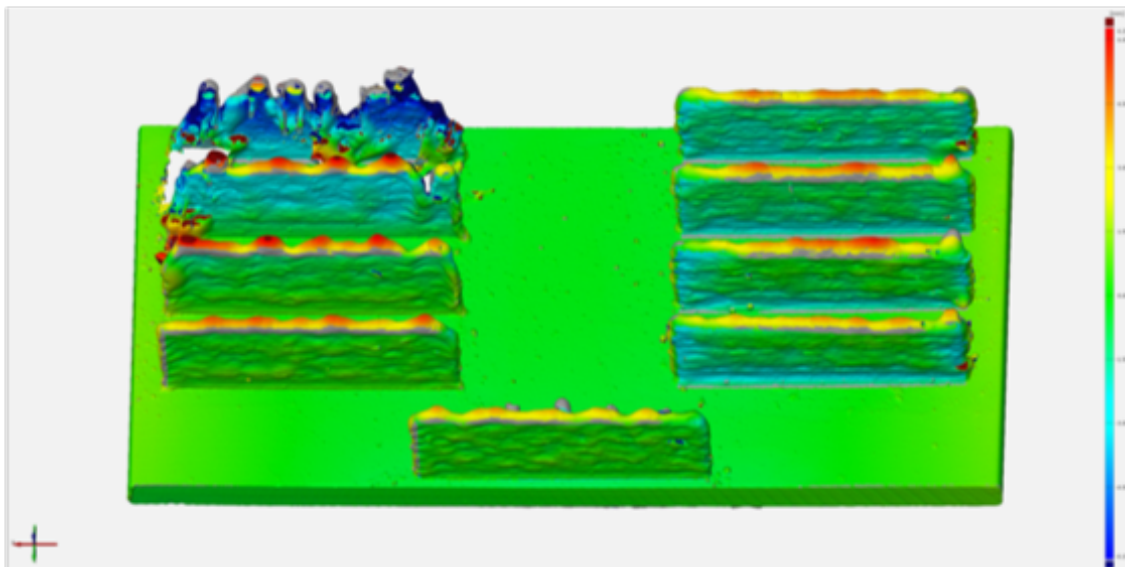


Figure 54: Top view of the geometry.

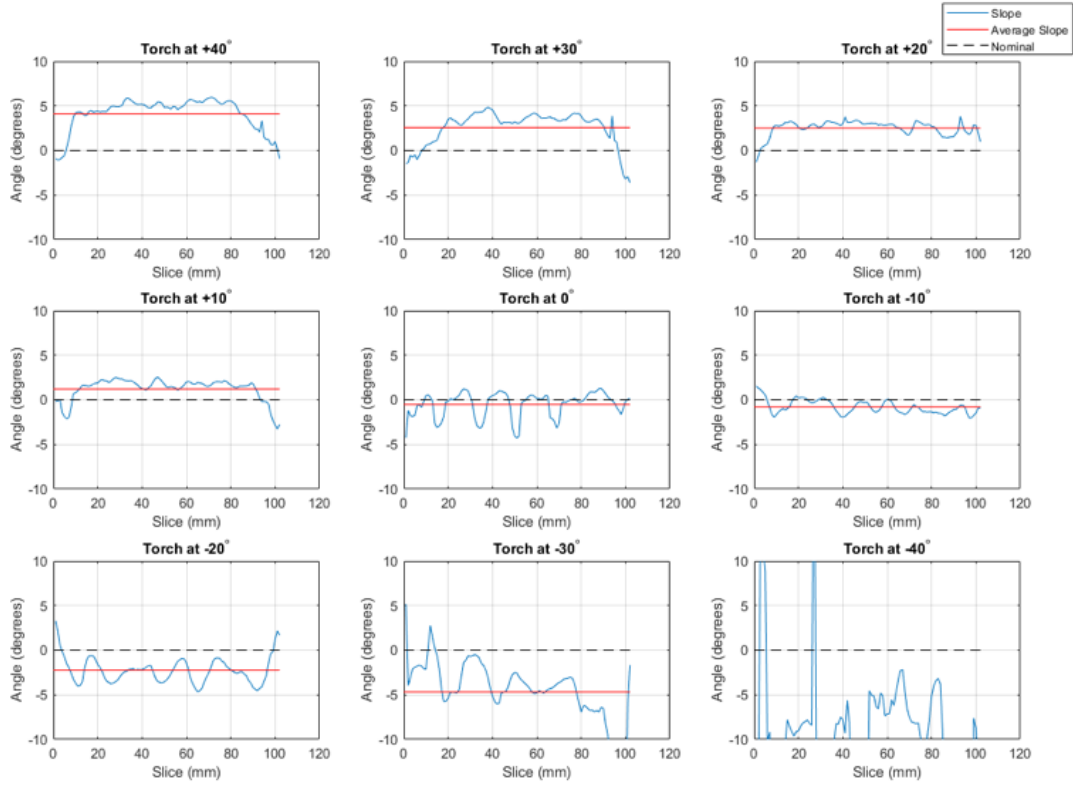


Figure 55: Slope calculations for each of the single walls from varying torch angles. This corresponds to the slope of the linear approximation of the top and bottom surface center line.

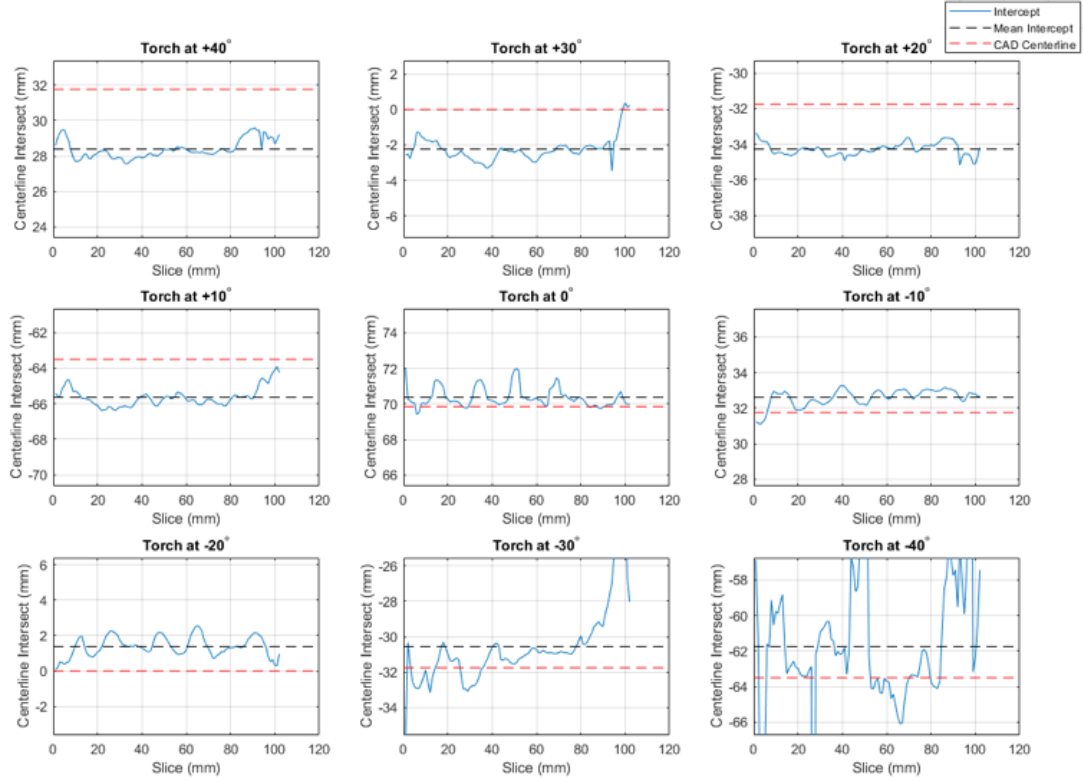


Figure 56: Deviation calculations for each of the single walls from varying torch angles. This corresponds to the slope intercept of the linear approximation of the top and bottom surface center line.

C Corrected Half Cylinder Metrology Results

C.1 Half Cylinder Metrology Front

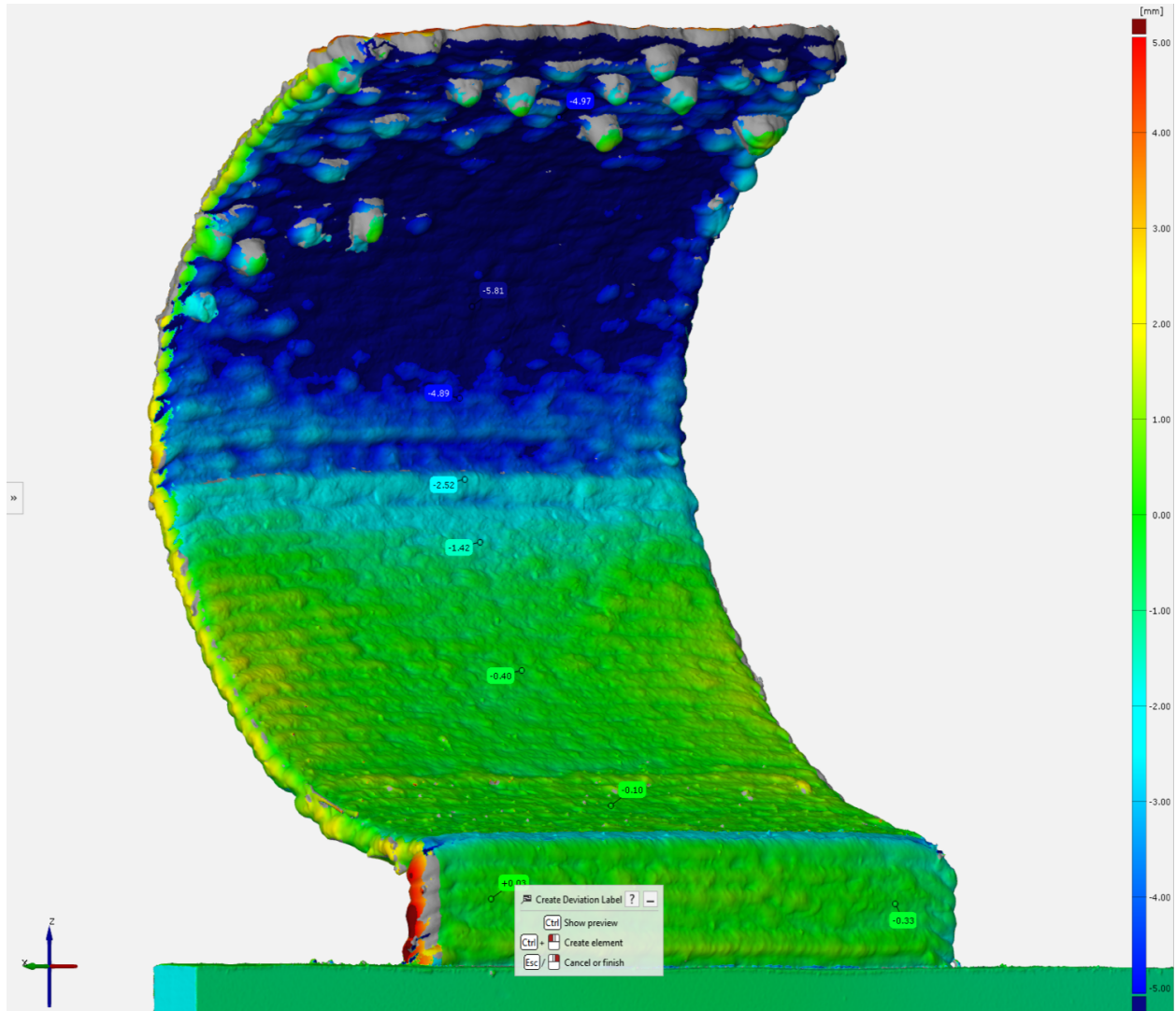


Figure 57: Metrology analysis of the corrected half cylinder. Red represents overbuild, blue represents under-build, and green represents nominal. The comparison CAD is the same used to generate the first half cylinder.

C.2 Half Cylinder Metrology Back

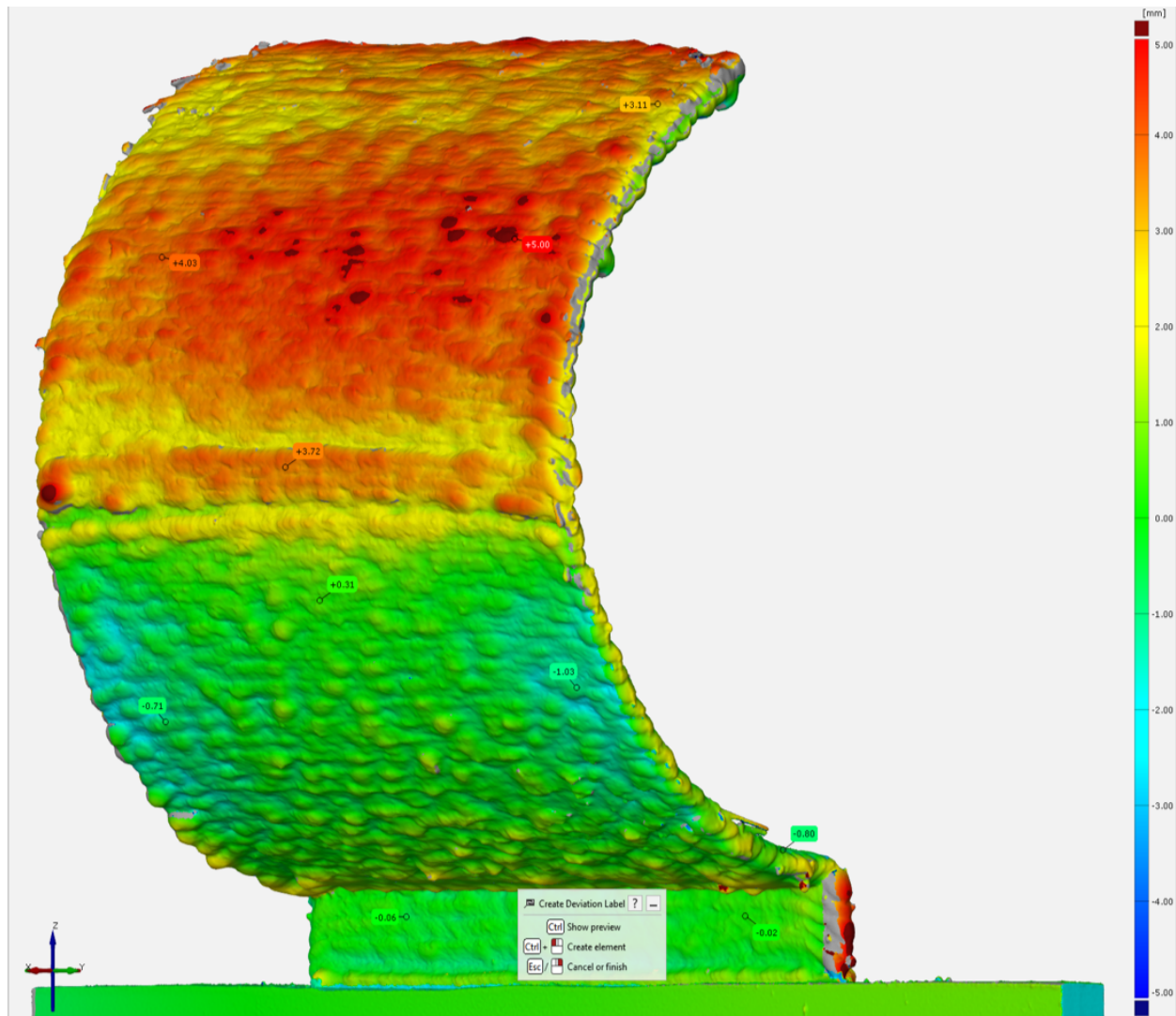


Figure 58: Metrology analysis of the corrected half cylinder. Red represents overbuild, blue represents under-build, and green represents nominal. The comparison CAD is the same used to generate the first half cylinder.

C.3 Half Cylinder Metrology Side

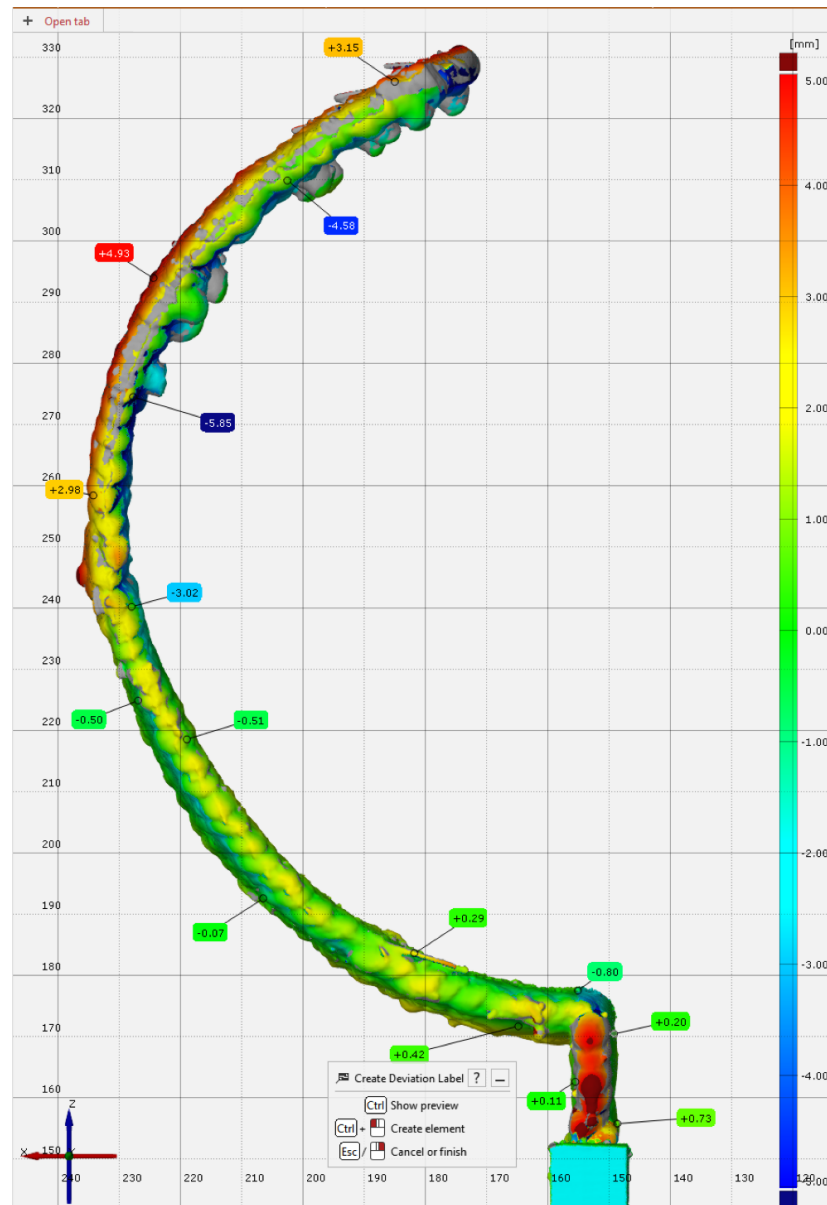


Figure 59: Metrology analysis of the corrected half cylinder. Red represents overbuild, blue represents under-build, and green represents nominal. The comparison CAD is the same used to generate the first half cylinder.

D Code Examples and Snippets

All of the code can be found on the University of Tennessee Arc GitHub. These repositories are being updated as new functionalities are added for path planning.

<https://github.com/utk-arc-lab>

D.1 Path Planner Software

Listing 1: This is an example file of all the waypoint algorithms used for updating specific positions and orientations of waypoints. These functions can be nested within the framework to have segment level operations call these functions to apply corrections as necessary.

```
1 classdef WaypointAlgorithms
2     methods(Static)
3
4         function vector_between_points = GetVectorBetweenPoints(point1, point2)
5             if(~isa(point1, 'Waypoint') || ~isa(point2, 'Waypoint'))
6                 fprintf('WaypointAlgorithms::GetVectorBetweenPoints: Inputs
7                     not all Waypoints\n');
8                 vector_between_points = [0,0,0];
9                 return;
10             end%if
11
12             vector_between_points(1) = point2.x - point1.x;
13             vector_between_points(2) = point2.y - point1.y;
14             vector_between_points(3) = point2.z - point1.z;
15
16         end%func GetVectorBetweenPoints
17
18         function distance_between_points = GetDistanceBetweenPoints(point1, point2)
19             if(~isa(point1, 'Waypoint') || ~isa(point2, 'Waypoint'))
20                 fprintf('WaypointAlgorithms::GetDistanceBetweenPoints:
21                     Inputs not all Waypoints\n');
22                 distance_between_points = 0;
23                 return;
24             end%if
25
26             x1 = point1.x;
27             y1 = point1.y;
28             z1 = point1.z;
29             x2 = point2.x;
30             y2 = point2.y;
31             z2 = point2.z;
```



```

29         distance_between_points = sqrt((x2-x1)^2 + (y2-y1)^2 + (z2-z1)^2);
30
31     end%func GetDistanceBetweenPoints
32
33     function midpoint = GetMidpoint(point1,point2)
34         if(~isa(point1,'Waypoint') || ~isa(point2,'Waypoint'))
35             fprintf('WaypointAlgorithms::GetMidpoint: Inputs not all
36                     Waypoints\n');
37             midpoint = null;
38             return;
39         end%if
40
41         midpoint = WaypointAlgorithms.GetPointBetween(point1,point2,0.5);
42
43     end%GetMidpoint
44
45     function between_point = GetPointBetween(point1,point2,percent_along_line)
46         if(~isa(point1,'Waypoint') || ~isa(point2,'Waypoint'))
47             fprintf('WaypointAlgorithms::GetPointBetween: Inputs 1 & 2
48                     not Waypoints\n');
49             midpoint = null;
50             return;
51         end%if
52         if(~(0 <= percent_along_line <= 1))
53             fprintf('WaypointAlgorithms::GetPointBetween: Input 3 not
54                     0-1\n');
55             midpoint = null;
56             return;
57         end%if
58
59         n = (1 - percent_along_line);
60
61         x = point2.x - n * (point2.x - point1.x);
62         y = point2.y - n * (point2.y - point1.y);
63         z = point2.z - n * (point2.z - point1.z);
64
65         quaternion_1 = Utils.NormalizeQuaternion(point1.torch_quaternion);
66         quaternion_2 = Utils.NormalizeQuaternion(point2.torch_quaternion);
67
68         torch_quaternion = slerp(quaternion_1,quaternion_2,
69                                 percent_along_line);
70         %torch_quaternion = quaternion_1;
71
72         speed = n * (point2.speed - point1.speed);
73         between_point = Waypoint(x,y,z,torch_quaternion,speed);

```



```

70
71     end%func GetPointBetween
72
73     function [x,y,z,a,b,c] = GetWaypointElements(waypoint)
74         if(~isa(waypoint, 'Waypoint'))
75             fprintf('WaypointAlgorithms::GetWaypointElements: Input not
76                 a waypoint\n');
77             x = [];
78             y = x;
79             z = x;
80             a = x;
81             b = x;
82             c = x;
83             return;
84         end%if
85
86         x = waypoint.x;
87         y = waypoint.y;
88         z = waypoint.z;
89         a = waypoint.a;
90         b = waypoint.b;
91         c = waypoint.c;
92     end%func GetWaypointElements
93
94     function [x,y,z,a,b,c] = GetShiftedWaypointElements(waypoint)
95         if(~isa(waypoint, 'Waypoint'))
96             fprintf('WaypointAlgorithms::GetShiftedWaypointElements:
97                 Input 1 not a waypoint\n');
98             x = [];
99             y = x;
100             z = x;
101             a = x;
102             b = x;
103             c = x;
104             return;
105         end%if
106
107         shift = waypoint.shift;
108         x = waypoint.x + shift.dx;
109         y = waypoint.y + shift.dy;
110         z = waypoint.z + shift.dz;
111
112         [a,b,c] = Utils.GetZYZEulerAnglesFromRotationMatrix(waypoint.R);
113         a = a + shift.da;
114         b = b + shift.db;

```

```

113         c = c + shift.dc;
114     end%func GetShiftedWaypointElements
115
116     function UpdateWaypointPosition(waypoint,new_x,new_y,new_z)
117         if(~isa(waypoint,'Waypoint'))
118             fprintf('WaypointAlgorithms::UpdateWaypointPosition: Input 1 is not a
119                 waypoint\n');
119             return;
120         end%if
121
122         waypoint.x = new_x;
123         waypoint.y = new_y;
124         waypoint.z = new_z;
125
126     end%func UpdateWaypointPosition
127
128     function UpdateWaypointRotation(waypoint,new_R)
129         if(~isa(waypoint,'Waypoint'))
130             fprintf('WaypointAlgorithms::UpdateWaypointPosition: Input 1 is not a
131                 waypoint\n');
131             return;
132         end%if
133
134         column1_denominator = sqrt((new_R(1,1).^2)+(new_R(2,1).^2)+(new_R(3,1).^2));
135         column2_denominator = sqrt((new_R(1,2).^2)+(new_R(2,2).^2)+(new_R(3,2).^2));
136         column3_denominator = sqrt((new_R(1,3).^2)+(new_R(2,3).^2)+(new_R(3,3).^2));
137
138         if column1_denominator ~= 0
139             new_R(1,1) = new_R(1,1)/column1_denominator;
140             new_R(2,1) = new_R(2,1)/column1_denominator;
141             new_R(3,1) = new_R(3,1)/column1_denominator;
142         else
143             new_R(1,1) = 1;
144             new_R(2,1) = 0;
145             new_R(3,1) = 0;
146         end
147
148         if column2_denominator ~= 0
149             new_R(1,2) = new_R(1,2)/column2_denominator;
150             new_R(2,2) = new_R(2,2)/column2_denominator;
151             new_R(3,2) = new_R(3,2)/column2_denominator;
152         else
153             new_R(1,2) = 0;
154             new_R(2,2) = 1;
155             new_R(3,2) = 0;

```

```

156         end
157
158         if column3_denominator ~= 0
159             new_R(1,3) = new_R(1,3) ./ column3_denominator;
160             new_R(2,3) = new_R(2,3) ./ column3_denominator;
161             new_R(3,3) = new_R(3,3) ./ column3_denominator;
162         else
163             new_R(1,3) = 0;
164             new_R(2,3) = 0;
165             new_R(3,3) = 1;
166         end
167
168         waypoint.R = new_R;
169
170     end%func UpdateWaypointRotation
171
172     function UpdateWaypointSpeed( waypoint , new_speed)
173         if (~isa(waypoint, 'Waypoint'))
174             fprintf('WaypointAlgorithms::UpdateWaypointPosition: Input 1 is not a
175                     waypoint\n');
176             return;
177         end%if
178
179         waypoint.speed = new_speed;
180     end%func UpdateWaypointSpeed
181
182     function RotateAboutToolFrameAxis(waypoint , degrees_to_rotate , axis_name)
183         if (~isa(waypoint, 'Waypoint'))
184             fprintf('WaypointAlgorithms::RotateAboutToolFrameAxis: Input 1 not a
185                     waypoint\n');
186             return;
187         end%if
188
189         theta = degrees_to_rotate;
190         axis_name = lower(axis_name);
191
192         switch axis_name
193             case 'x'
194                 R = [1,0,0
195                     0,cosd(theta),-1 * sind(theta)
196                     0,sind(theta),cosd(theta)];
197             case 'y'
198                 R = [cosd(theta),0,sind(theta)
199                     0,1,0

```

```

199         -1*sind(theta),0,cosd(theta)];
200     case 'z'
201         R = [cosd(theta),-1*sind(theta),0
202             sind(theta),cosd(theta),0
203             0,0,1];
204     otherwise
205         fprintf('WaypointAlgorithms::RotateAboutToolFrameAxis: Axis
                name not recognized\n');
206         return;
207     end%switch
208
209     waypoint.R = waypoint.R * R;
210 end%func RotateAboutToolFrameAxis
211
212 function SetShift(waypoint, shift)
213     if(~isa(waypoint, 'Waypoint'))
214         fprintf('WaypointAlgorithms::SetShift: Input 1 not a waypoint\n');
215         return;
216     end%if
217
218     if(~isa(shift, 'Shift'))
219         fprintf('WaypointAlgorithms::SetShift: Input 2 not a Shift\n');
220         return;
221     end%if
222
223     waypoint.shift = shift;
224 end%func SetShift
225
226 function TranslateWaypoint(waypoint, x_translate, y_translate, z_translate)
227     if(~isa(waypoint, 'Waypoint'))
228         fprintf('WaypointAlgorithms::TranslateWaypoint: Input 1 is not a waypoint\n'
                );
229         return;
230     end%if
231
232     waypoint.x = waypoint.x + x_translate;
233     waypoint.y = waypoint.y + y_translate;
234     waypoint.z = waypoint.z + z_translate;
235 end%func TranslateWaypoint
236
237 end%methods
238 end%class WaypointAlgorithms

```

D.2 Net Shape Analysis Software

Listing 2: This file was used for analyzing the linear sections of the wall to determine the ideal torch angle. This is the method file for identifying the average wall slope and intercept for analysis.

```
1  classdef CrossSectionAnalysisMethods
2      properties (Constant)
3
4      end%const
5      methods (Static)
6          function wall_height = GetWallHeight(cross_section, height_axis)
7              if (~isa(cross_section, 'GOMCrossSection'))
8                  fprintf('CrossSectionMethods::GetWallHeight: Input not a
9                      GOMCrossSection\n');
10                 return;
11             end%if
12
13             height_axis = lower(height_axis);
14             switch height_axis
15                 case 'x'
16                     wall_height = max(cross_section.x) - min(
17                         cross_section.x);
18                 case 'y'
19                     wall_height = max(cross_section.y) - min(
20                         cross_section.y);
21                 case 'z'
22                     wall_height = max(cross_section.z) - min(
23                         cross_section.z);
24                 otherwise
25                     fprintf('CrossSectionMethods::GetWallHeight: Height
26                         Axis input not recognized\n');
27                 end%switch
28             end%func GetWallHeight
29
30             function wall_height_vector = GetWallHeightForSet(cross_section_set,
31                 height_axis)
32                 n_points = length(cross_section_set);
33                 wall_height_vector = zeros(1, n_points);
34
35                 for i = 1:n_points
36                     wall_height_vector(i) = CrossSectionAnalysisMethods.
37                         GetWallHeight(cross_section_set{i}, height_axis);
38                 end%for i
39             end%func GetWallHeightForSet
```

```

33
34 function [slope_vector, intercept_vector] = GetWallCenterLinesForSet(
    cross_section_set, height_axis)
35     n_points = length(cross_section_set);
36     slope_vector = zeros(1, n_points);
37     intercept_vector = slope_vector;
38
39     for i = 1:n_points
40         [line_slope, line_intercept] = CrossSectionAnalysisMethods.
            GetWallCenterLine(cross_section_set{i}, 'z', false);
41         slope_vector(i) = line_slope;
42         intercept_vector(i) = line_intercept;
43     end%for i
44
45 end%func GetWallCenterLinesForSet
46
47 function [line_slope, line_intercept] = GetWallCenterLine(cross_section,
    height_axis, bool_plot)
48     if (~isa(cross_section, 'GOMCrossSection'))
49         fprintf('CrossSectionMethods::GetWallCenterLine: Input not a
            GOMCrossSection\n');
50         return;
51     end%if
52     if (nargin == 2)
53         bool_plot = true;
54     end%if
55
56     cross_section_subset = CrossSectionMethods.
        GetCrossSectionSubsetInAxisRange(cross_section, height_axis);
57     [top_half, bottom_half] = CrossSectionAnalysisMethods.
        GetTopAndBottomOfWall(cross_section_subset, height_axis);
58     if (length(top_half.x) > 0 && length(bottom_half.x) > 0)
59         top_mdl = fitlm(top_half.z, top_half.y);
60         bottom_mdl = fitlm(bottom_half.z, bottom_half.y);
61
62         % y = mx + b
63         top_b = top_mdl.Coefficients.Estimate(1);
64         top_m = top_mdl.Coefficients.Estimate(2);
65         top_r2 = top_mdl.Rsquared.Ordinary;
66         bottom_b = bottom_mdl.Coefficients.Estimate(1);
67         bottom_m = bottom_mdl.Coefficients.Estimate(2);
68         bottom_r2 = bottom_mdl.Rsquared.Ordinary;
69
70         avg_b = (top_b + bottom_b) / 2;
71         avg_m = (top_m + bottom_m) / 2;

```

```

72
73         top_z = [min(top_half.z),max(top_half.z)];
74         top_y = top_b + top_m .* top_z;
75
76         bottom_z = [min(top_half.z),max(top_half.z)];
77         bottom_y = bottom_b + bottom_m .* bottom_z;
78
79         avg_z = [mean([bottom_z(1),top_z(1)]),mean([bottom_z(2),
80               top_z(2)])];
81         avg_y = avg_b + avg_m .* avg_z;
82
83         if(bool_plot)
84             fprintf('Top Line: y = %1.3fx + %1.3f, R2 = %1.3f\n',
85                   ,top_m,top_b,top_r2);
86             fprintf('Bottom Line: y = %1.3fx + %1.3f, R2 = %1.3f
87                   \n',bottom_m,bottom_b,bottom_r2);
88             fprintf('Center Line: y = %1.3fx + %1.3f\n',avg_m,
89                   avg_b);
90
91             figure;
92             plot(top_half.z,top_half.y,'k');
93             hold on;
94             plot(bottom_half.z,bottom_half.y,'b');
95             plot(top_z,top_y,'r—');
96             plot(bottom_z,bottom_y,'r—');
97             plot(avg_z,avg_y,'m-');
98             hold off;
99             legend('Top','Bottom');
100             title(cross_section_subset.file_path);
101         end%if
102
103         line_slope = avg_m;
104         line_intercept = avg_b;
105     else
106         fprintf('CrossSectionAnalysisMethods::GetWallCenterLine: Top
107               and Bottom Halves not recognized\n');
108         line_slope = NaN;
109         line_intercept = NaN;
110     end%if
111 end%func GetWallCenterLine
112
113 function [top_half,bottom_half] = GetTopAndBottomOfWall(cross_section_subset
114     ,height_axis)
115     if(~isa(cross_section_subset,'GOMCrossSection'))

```

```

110         fprintf('CrossSectionMethods::GetTopAndBottomOfWall: Input
111                 not a GOMCrossSection\n');
112         top_half = [];
113         bottom_half = [];
114         return;
115     end%if
116
117     n_points = length(cross_section_subset.x) - 1;
118     distances = zeros(1,n_points);
119
120     for i = 1:n_points
121         x1 = cross_section_subset.x(i);
122         y1 = cross_section_subset.y(i);
123         z1 = cross_section_subset.z(i);
124         x2 = cross_section_subset.x(i+1);
125         y2 = cross_section_subset.y(i+1);
126         z2 = cross_section_subset.z(i+1);
127         distances(i) = Utils.Distance3(x1,y1,z1,x2,y2,z2);
128     end%for i
129
130     % figure;
131     % plot(distances);
132
133     d_dist = abs(diff(distances));
134     flags = find(d_dist > 1);
135     flags = [1,flags,length(distances)];
136     lengths = flags(2:end) - flags(1:end-1);
137
138     if(length(lengths) < 2)
139         [~,flag] = max(distances);
140         top_half_indices = 1:flag;
141         bottom_half_indices = flag+1:length(cross_section_subset.x);
142     else
143         [~,biggest_object_indices] = maxk(lengths,2);
144         biggest_object_indices = biggest_object_indices + 1;
145
146         top_half_indices = flags(biggest_object_indices(1)-1):flags(
147             biggest_object_indices(1));
148         bottom_half_indices = (flags(biggest_object_indices(2)-1) +
149             1):flags(biggest_object_indices(2));
150     end%if
151
152     % [~,flag] = max(distances);
153
154     % if(length(flag) > 1)

```



```

152         fprintf(' CrossSectionMethods::GetTopAndBottomOfWall: More
           than one flag!\n');
153         top_half = [];
154         bottom_half = [];
155         return;
156     % end%if
157
158     % top_half_indices = 1:flag;
159     % bottom_half_indices = flag+1:length(cross_section_subset.x);
160
161     top_half = CrossSectionMethods.
           CreateCrossSectionSubsetWithLogicalIndices(cross_section_subset ,
           top_half_indices);
162     bottom_half = CrossSectionMethods.
           CreateCrossSectionSubsetWithLogicalIndices(cross_section_subset ,
           bottom_half_indices);
163     end%func GetTopAndBottomOfWall
164 end%static methods
165 end%class CrossSectionAnalysisMethods

```

D.3 Thermal Analysis Software

Listing 3: This file is the evaluation script used to help iterate through new examples of the code. All of the main parameters can be seen, and the calling functions necessary to run the script.

```

1  clc , clear all , close all;
2  list = [2 5 10];
3
4
5  for val = list
6      close all;
7
8      % Set up custom properties
9      t = ThermalPath;
10     t.bead_height = 2.253e-3; %m
11     t.bead_width = 6e-3; %m
12
13     t.n_layers = val; %# of layers
14     t.nodes_per_layer = 10; % # per layer
15     t.wall_length = 152.4e-3; % m
16
17     t.base_width = 152.4e-3; % m

```

```

18     t.base_length = 304.8e-3; % m
19     t.base_thick = 25e-3; % m
20     t.base_origin = [0,0]; % location determined by mm
21
22     t.wall_origin = [(t.base_length - t.wall_length)./2,t.base_thick]; %m
23
24     ThermalPathBuilder.BuildSolidWall(t);
25     % ThermalPathBuilder.BuildCastle(t);
26     % t.contours{end}.waypoints = flip(t.contours{end}.waypoints);
27
28     p = ThermalSimProperties(t); % default
29     % Options
30     p.bool_activate_nodes_iteratively = true; % turns on node activation k
31     p.bool_enable_internal_heat_generation = true; % has heat generation per node
32     % Parameters
33     p.melt_temp = 1800; %Kelvin from 1450 C, based from above mild steel melt temps
34     p.density = 7870; %low-carbon steel 7.87 g/cm3 converted to kg/m3 AISI 1010
35     p.Cp = 600; % mild steel 510 J/kg K (Specific Heat)
36     p.k = 25; % mild steel 1%C average vale W/m-K (Thermal Conductivity)
37     p.ambient_T = 293; %20Deg C to Kelvin
38     p.eff = .5;
39
40     p.weld_time_offset = 0.01; % sec
41     p.baseplate_convection_coefficient = 30; %W/m2-K
42
43     % Run the Model and build it up from here...
44     thermalmodel = ThermalSim.ConfigureSingleWallSim(p);
45
46     sim_time = 120.*(t.n_layers); % s
47     sim_fps = 20;
48
49     [R,tlist] = ThermalSim.SolveSingleWallSim(thermalmodel,sim_time,sim_fps);
50
51     data_title = sprintf('ThermalSim Layer(s)%f',val);
52     ThermalPlotter.PDECustomAnimate(p,thermalmodel,R,tlist,true,data_title);
53
54
55     save(data_title);
56 end%for q_dot
57
58 load handel
59 sound(y,Fs)

```

Listing 4: This file is the heart of the thermal simulation which activates the thermal conductivity as the part moves on, as well as the internal heat generation. These functions significantly slow the thermal analysis, but are necessary to accomplish the moving heat source during the build.

```

1  classdef ActivationFunctions
2      methods(Static)
3          function thermal_conductivities = NodeActivationFunction(location, state)
4              global kActivateTime;
5              global k_mat;
6
7              if any(isnan(state.time))
8                  thermal_conductivities = nan(size(state.u));
9                  return;
10             end
11             face_indices = location.subdomain;
12
13             thermal_conductivities = zeros(size(face_indices));
14             for i = 1:length(thermal_conductivities)
15                 current_face = face_indices(i);
16
17                 if(state.time > kActivateTime(current_face))
18                     thermal_conductivity = k_mat;
19                 else
20                     thermal_conductivity = 0;
21                 end%if
22
23                 thermal_conductivities(i) = thermal_conductivity;
24             end%for i
25         end%func NodeActivationFunction
26
27         function internal_heat_generation = InternalHeatingFunction(location, state)
28             global kStartTime;
29             global kEndTime;
30             global Q_dot;
31
32             if any(isnan(state.time))
33                 internal_heat_generation = nan(size(state.u));
34                 return;
35             end%if
36             face_indices = location.subdomain;
37
38             internal_heat_generation = zeros(size(face_indices));
39             for i = 1:length(internal_heat_generation)

```

```

40         current_face = face_indices(i);
41
42         start_time = kStartTime(current_face);
43
44         end_time = kEndTime(current_face);
45
46         if(state.time > start_time && state.time < end_time)
47             internal_heat = Q_dot;
48         else
49             internal_heat = 0;
50         end%if
51
52         internal_heat_generation(i) = internal_heat;
53     end%for i
54 end%func InternalHeatingFunction
55 end%Static methods
56 end%class

```

Vita

James Logan McNeil started his research career in High School, attending a chemistry research lab at the University of Tennessee as a part of Science Academy. During his undergraduate degree he worked part time during the school year and full time during the summer on research on biorobotics systems, particularly on the Tracking Fluoroscope System (TFS). His background in undergraduate research consisted of maintaining the LabVIEW real time control system and necessary CAD and electrical work on the system. After beginning his Masters and PhD at University of Tennessee under Dr. William R. Hamel, his specialty switched to additive manufacturing. Logan has experience is Laser Powder Bed Fusion of high nickel prime alloys with in-situ monitoring and ex-situ characterization, path planning for large scale additive manufacturing using wire and arc additive manufacturing, and full design to fabrication of tool molds using large scale additive manufacturing. Many of these projects were done under the direction of researchers at Oak Ridge National Labs at the Manufacturing Demonstration Facility. During his free time, Logan maintains many other responsibilities such as the Director and Coach of the Tennessee Rugby Academy in Knoxville and the East Tennessee Representative of the Tennessee Rugby Association board. He also enjoys hunting and fishing and spending time with his wife Hailey.