3D SPATIAL RECONSTRUCTION OF THERMAL
CHARACTERISTICS IN DIRECTED ENERGY DEPOSITION
THROUGH OPTICAL THERMAL IMAGING

A Thesis in
Mechanical Engineering
by
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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2014
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Abstract

An application to visualize thermal metrics extracted from coaxial thermal images in three dimensions during directed energy deposition is presented in this thesis. The extraction of thermal metrics is useful for correlation of microstructure for process monitoring and control of additive manufacturing. The thermal metrics attained from the coaxial images include the thermal gradient at the solidus to liquidus region, the maximum temperature in the melt pool, the melt pool pixel area, and the length-to-width ratio of the melt pool. The current procedure for part qualification in additive manufacturing is through destructive methods. The use of thermal metrics in a 3D spatial reconstruction allows for a non-destructive means to distinguish material microstructure. For this reconstruction, two Ti-6Al-4V L-shaped parts were deposited with a 1-bead wide deposition on one leg of the build and 3-bead wide deposition on the second leg of the build. A filtering scheme of the coaxial thermal images is utilized to produce melt pools with distinguishable solidus to liquidus regions. The acquisition of laser location during deposition is used to create a three dimensional representation of the calculated thermal metrics. Differences in thermal metric values between separate legs of the L-shaped parts express changes in the thermal history and hence the microstructure development for the transient and steady state regions of melt pool movement. For process monitoring, the cross sectional cuts of the three dimensional representation of thermal metrics can correlate to variations in material microstructure from the cross sectional cuts of actual L-shaped builds.
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Acknowledgments

I am very appreciative to my thesis advisors, Dr. Panagiotis Michaleris and Dr. Edward Reutzel, for their guidance during the course of my research work. Additional acknowledgement goes to America Makes and ARL Penn State for fellowship and funding for the experiments. I would like to acknowledge Dr. Abdalla Nassar for his assistance in operating the LENS® system during experiments and for his recommendations during the entire process. I would like to thank Jim Craig and Tom Wakeman from Stratonics for the use of their thermal imaging system and their continual input. I would like to express my gratitude to my family and friends for their endless prayer, encouragement, and support during my entire graduate studies. Lastly, but truly first, to Jesus Christ for the life that I have been given.
Chapter 1

Introduction

Directed energy deposition is an additive manufacturing (AM) process that is used to create near-net shape components through the build up of successive layers. Additive manufacturing is an attractive option in the aerospace and defense industries due to the design flexibilities that it enables. Additive manufacturing processes can also deliver lead time enhancements, low buy-to-fly ratios, and minimal material gradients throughout the builds compared to conventional forged and machined production processes. Process deficiencies add drawbacks to additive manufacturing that may result in inconsistent parts. In order to produce consistent parts, thermal imaging is a beneficial tool that produces a full thermal history from coaxial and/or side view images. A full understanding of the thermal images is crucial to deliver process monitoring for “qualify as you build” and controller options that can regulate microstructure and material properties. This work is a portion of a larger effort to define thermal metrics that are obtained from coaxial thermal images during additive manufacturing processes and in turn predict microstructure and material properties of AM deposited materials.

In related work, solidification map and process map approaches have been proposed for microstructure prediction by Hunt [1], Gaumann [2], Klingbeil [3], Birnbaum [4], Beuth [5], Bontha [6] and Gockel [7]. These methods to predict microstructure have
been formulated through a combination of experimental procedures and modeling tech-
niques. Kurz et al. analyzed thermal gradients and cooling rates used for construction
of solidification microstructure-processing maps for the superalloy CMSX 4 [8]. Addi-
tionally, various thermal imaging methods have been administered to obtain thermal
histories from coaxial or side view images. Griffith et al. used side view and coaxial
imaging in the LENS© system for deposition of H13 stainless steel to acquire melt pool
temperatures and gradients [9]. Xiong et al. viewed temperature profiles at various build
layers while predicting melt pool area, melt pool size and maximum temperature of
tungsten carbide-cobalt [10]. Bardin et al. implemented a two color thermal imaging
system for non-contact temperature measurements in stainless steel conduction welding
[11]. Hofmeister et al. investigated coaxial thermal images with microstructural analysis
of 316 stainless steel and H13 tool steel in LENS© processing [12].

Analysis of thermal profiles, thermal metrics, and melt pool dimensions during
laser-based AM and similar processes have also been performed through modeling tech-
niques. Melt pool dimensions have been analyzed by Hu [13], Fathi [14], Sudnik [15], and
Liu [16] through modeling approaches. Vasinonta et al. used a thermo-mechanical model
that in part was used to predict normalized melt pool length and width [17]. Alimardani
et al. used a 3D modeling approach to predict temperature profiles in a multilayer laser
solid freeform fabrication process for AISI 304L stainless steel [18]. Bai et al. developed
a double ellipsoid heat source model to perform thermal analysis of weld-based addi-
tive manufacturing with a side view thermal imaging calibration for deposition of AWS
ER70S-6 steel wire [19]. Wang et al. developed a two dimensional thermal finite element
model to predict temperature profiles in SS316 plates during deposition in the LENS® process [20]. Aggrangsi et al. viewed transient changes in the melt pool for thin-walled structures in the LENS® system for 304 stainless steel through 2D finite element modeling [21]. Ye et al. used a ThermaViz® thermal imaging system to validate temperatures of a 2D finite element model for a thin wall fabricated of AISI 316 stainless steel through LENS® processing [22]. Hofmeister investigated control of the LENS® process through a high speed video monitoring set-up to determine cooling rates within and around the melt pool for 316 stainless steel [23].

In addition to work done with process maps and thermal metrics, researchers have performed analysis and predictions of material microstructure and mechanical properties for additive manufacturing. Kobryn and Semiatin have evaluated microstructure of Ti-6Al-4V between metal-mold casting and direct laser fabrication [3]. Wu et al. viewed microstructure of Ti-6Al-4V builds in the LENS® process across a range of laser powers, scan speeds, and powder feed rates [24]. Zheng et al. performed a microstructural analysis in the LENS® system for H13 tool steel and examined the thermal behavior of the substrate and melt pool [25]. Davis and Klingbeil observed the effect of free edges on solidification microstructure for thin-walled [26] and 3D structures [27] for Ti-6Al-4V. Brandl et al. examined microstructure of Ti-6Al-4V for several process parameters for single bead deposition [28]. Additionally, Brandl et al. compared microstructure and mechanical properties of wire and powder based processes for deposition of Ti-6Al-4V [29]. Kelly implemented thermal and microstructural modeling of metal deposition processes with Ti-6Al-4V [30].
The prior work analyzed thermal metrics in mostly a modeling sense with limited thermal imaging investigation for validation of the respective models. The work in microstructure prediction has been done with the absence of a thermal imaging investigation. The previous work in thermal imaging provides substantial insight for materials other than the current interest of $\alpha/\beta$ Ti alloys.

In this work, coaxial thermal images recorded during the deposition of Ti-6Al-4V L-shaped builds are used to extract thermal metrics pertaining to resultant material microstructure. Large quantities of coaxial thermal imaging data are necessary to establish thermal histories throughout the entire deposition and to accurately describe the change in microstructure at distinct heights and locations of the build. The investigation of massive amounts of optical thermal imaging is set forth through methodology of data reduction. Effects of raw and filtered coaxial data are viewed in contrast for noise reduction of the melt pool solidus to liquidus region at the trailing edge. Consideration of the direction of motion of the melt pool delivers the importance of the distinct solidus to liquidus region. Analysis of coaxial thermal imaging melt pools affected by previously deposited material shows various thermal histories over the eight hatches of the L-shaped builds. Extraction of thermal metrics and combination with build locations offer a three dimensional representation for prediction to material microstructure. This work helps to bridge the gap between thermal metric evaluation and material microstructure prediction.
Chapter 2

Application to Coaxial Thermal Imaging

This chapter consists of an explanation of the experimental setup and the application and data reduction of the ThermaViz® coaxial images for implementation of thermal metric extraction. The experimental setup includes deposition and coaxial image acquisition. Data reduction consists of filtering of the coaxial images and interpretation of the melt pool characteristics.

2.1 Experimental Procedure

2.1.1 Deposition Process

In this work, directed energy deposition is performed in an Optomec® LENS® MR-7 system with a 500 W IPG Fiber Laser. Two L-shaped builds are constructed of Ti-6Al-4V on substrates measuring 7.62 cm by 7.62 cm by 0.635 cm. During deposition, the system operating power varies between 450 W for the and 350 W. The L-shaped builds shown in Figure 2.1 are formed with a 1-bead wide deposition for one leg of the build and a 3-bead wide deposition for the second leg. The variation in power of 450 W for the 1-bead wide leg and 350 W for the 3-bead wide leg delivers consistent height over the course of the 286 layers. Additionally, the 3-bead wide leg has a hatch spacing of
0.81 mm which maintains an average single pass height of 0.18 mm with the variability of the laser power. The Ti-6Al-4V powder is sieved to a -100/+325 sieve range, and the mass flow rate of the powder is set to 3 g/min.

Fig. 2.1. Physical parts of (a) 0 s delay and (b) 4 s delay builds

The LENS® processing chamber is hermetically sealed and purged with argon to achieve an environment with an oxygen content less than or equal to 4.8 parts per million for the two builds. An argon gas flow rate of 30 L/min for coaxial purge flow is used for protection of the laser optics while a gas flow rate of 4 L/min is used to deliver powder. The deposition head is positioned 0.93 cm above the deposition surface. At this height, the beam diameter is approximately 1.36 mm. The travel speed of the laser head is set to 63.5 cm/min, and Figure 2.2 portrays the travel path during deposition. The transition regions between legs and hatches maintain a constant travel speed during
processing. The dimensions of the completed part are 2.54 cm long for each of the legs and 5.08 cm tall. The main difference in processing between the two L-shaped builds is the delay time between layers. One build has a 0 s delay between forward and reverse passes while a 4 s delay is implemented at the completion of each layer for the second build. These delays take place at the completion of hatch 4 and hatch 8. The DMC code which defines the build path and specifications is included in Appendix A and Appendix B for the 0 s delay build and the 4 s delay build, respectively.

Fig. 2.2. The eight hatches of deposition path.
2.1.2 Coaxial Thermal Imaging of the Melt Pool

During the entire deposition of the L-shaped parts, coaxial thermal images of the melt pool are recorded using a Stratonics ThermaViz® camera. This system is a two-wavelength imaging pyrometer that stores each image originally as intensity values. The two wavelengths enable a temperature calibration so that each image is saved as a true temperature in Celsius. Each individual image contains 752 pixels wide by 480 pixels tall with each pixel storing an individual temperature value for a region within the coaxial field of view of 4-5 mm. These temperature values are stored within the respective ThermaViz® files as 8 bytes per pixel. Through conversion from binary to decimal, these temperature values are extracted from the ThermaViz® files and displayed using MATLAB® R2012a as a grayscale image with consistent image height and image width obtained in the header file of the ThermaViz® output file.

The acquisition of continual thermal images produces thermal videos over the course of the 5.08 cm tall builds. The 0 s delay build is recorded at 5 Hz, and the thermal video consists of 7,248 images requiring 10.47 GB of storage. The 4 s delay build is recorded at 2 Hz, and the thermal video consists of 5,090 images requiring 7.35 GB of storage. The reduction in recording frequency is to account for the acquisition of the two entire builds with storage limitations. The ThermaViz® optics and the laser optics are aligned along the same axis that creates a moving reference frame as the deposition head travels. Interfacing between the LENS® system and the ThermaViz® system is implemented for saving of the coaxial image location in relation to the physical three
dimensional position within the build. Voltage measurements are recorded with the coaxial images corresponding to X, Y, and Z axis locations and converted to location with 1.77 V/cm scaling. At the working distance, each pixel corresponds to a surface area that measures 5.25 µm by 5.25 µm. In order to acquire the melt pool in the image, the thermal imaging system is set at a specific intensity threshold that determines the upper and lower cutoffs for the temperature range for the entire set of images. For this set of thermal images, the lower temperature cutoff is set at 150 °C and the upper temperature cutoff is set to 3500 °C. These temperature cutoffs define the range of temperatures that are within the melt pool and adjacent to the melt pool. A single raw coaxial image is plotted in MATLAB® with a solidus to liquidus region in yellow and a blue pixel denoting the position of the maximum temperature location in Figure 2.3. The solidus to liquidus region is defined as all the pixels with temperatures between the solidus and liquidus temperatures of 1620 °C and 1654 °C, respectively. The temperature range used to define the solidus to liquidus transition is found in reference [6].
2.2 Filtering of Thermal Images

The coaxial thermal images contain a certain level of noise, like any set of experimental data, for the temperatures ranging from the center of the melt pool to the outer edges of the data that are defined by the intensity thresholds. At the outer most edges of the melt pool and within the solidus to liquidus region visible in Figure 2.4, “salt and pepper” noise alters the ability to calculate accurate thermal metrics. From pixel to pixel, there is noise starting in the melt pool center extending to the solidus to liquid region of the melt pool and even ranging to the lower temperature threshold. If
a particular pixel were to drop below the temperature threshold of 150 °C, that pixel registers 0 °C. Theoretically, the temperature profile from the melt pool center to the solidus to liquidus region is a continuous decrease in temperature in all directions.

Fig. 2.4. Noisy solidus to liquidus region.

2.2.1 Filtering within a Frame

For smoother data over the entirety of the individual coaxial images, filtering is required to diminish the noise. A two dimensional median filtering approach represented in Figure 2.5 has been implemented to reduce the noise seen in each image. Essentially, the approach uses a window of $n$ by $n$ pixels, finds the median of the window, and
replaces the center value of the window with the median. The median filtering approach also pads the edges of the image with zeros which can produce distortion at the edges of the frames. Fortunately, the interest at the edges of the image is minuscule since all thermal metrics are measured within the solidus to liquidus region of the melt pool, and ultimately, solidification of the Ti-6Al-4V has already occurred beyond the tail of the melt pool. Implementation of the two dimensional median filtering approach is an effective way in image processing to both reduce noise and preserve edges of the matrices.

Fig. 2.5. 2D median coaxial filtering method for n=11.
Various window sizes have been analyzed in [31, 32] for 2D median filter approaches ranging from \( n=3 \) to \( n=17 \). The effect of window size on noise reduction at the solidus to liquidus region can be seen in Figure 2.6 in which square 2D median filters are used with square dimensions of \( n=3, 5, 7, 9, \) and 11 pixels, respectively. Likewise, Figure 2.8 is a representation of the noise at the trailing edge of the melt pool for each of the five window sizes. This noise representation shows the pixel distance of 25 pixels above and below the melt pool center and the corresponding distances from each pixel to the solidus to liquidus region at the trailing edge of the melt pool. A decrease in noise is shown as the window size increases until a minimal amount of noise is seen in Figure 2.8(e) and Figure 2.8(f) for window sizes of \( n=9 \) and \( n=11 \). Figure 2.7 represents the coordinate system positioned at the melt pool center for the noise reduction analysis. \( X' \) is the longitudinal distance from the melt pool center to the trailing edge, and \( Y' \) is the transverse distance along the melt pool center.
Fig. 2.6. Median filtering of the melt pool.
Fig. 2.7. Coordinate system for median filtering noise reduction.
Fig. 2.8. Median filtering noise reduction at the solidus to liquidus region.
The resultant reduction of noise at the solidus to liquidus region at the trailing edge of the melt pool can be seen in Figure 2.9 for a window size of n=11. For noise reduction within each frame, a window size of n=11 is used for the entirety of the two thermal videos.

Fig. 2.9. Filtered solidus to liquidus region.

2.2.2 Filtering across Entire Thermal Videos

In addition to filtering within an individual frame, another level of filtering is implemented from frame to frame. During the deposition process, there are periods of
time that produce coaxial images that either appear as blank or saturated, as shown in
Figure 2.10. Throughout the build, the laser turns off and on again at the end of each
layer. If the image acquisition of the coaxial camera and the instance in which the laser
turns off occur at the same time, the result is a blank thermal image in which the melt
pool is reforming. The white images occur due to the ThermaViz® camera intermittent
hardware resetting, resulting in intensity spikes over the whole image. Additionally
since the coaxial field of view is restricted to a 4-5 mm space, several melt pools display
solidus to liquidus regions that are beyond the field of view. These cases are all omitted
from further analysis. The location of the laser corresponding to the omitted images are
represented in three dimensions in Figure 2.11. For the 0 delay, 9.73% of the thermal
images are omitted. For the 4 s delay build, 10.81% of the thermal images are omitted.

Fig. 2.10. Actual coaxial thermal images of (a) blank and (b) saturated images
Fig. 2.11. Omitted image locations from (a) 0 s and (b) 4 s delay builds in red

2.3 Melt Pool Movement

2.3.1 Direction Determination

The most interesting region of the melt pool is the solidus to liquidus region at the trailing edge of melt pool since this is the location in which material microstructure grows perpendicular from the solidus to liquidus region. The width of the solidus to liquidus region shows a direct relationship to the thermal gradient across the region. A
thicker solidus to liquidus region corresponds to a lower thermal gradient while a thinner solidus to liquidus region corresponds to a higher thermal gradient. Additionally, the lowest thermal gradient can be found at the trailing edge of the melt pool.

Determining the location of the melt pool trailing edge in the image is extremely important due to the growth of microstructure from this region. Therefore since the data is post processed in relation to acquisition, the eight hatches in each build can be separated based on X, Y, and Z axis locations and travel direction attained by referencing an individual coaxial image’s current location and the image’s previous location. For process monitoring, an instantaneous velocity should be stored for the coaxial image for direction determination as discussed in Chapter 6.

Without knowing the physical location of each of the melt pools in the build, a combination of the coaxial thermal image and the melt pool direction is required to compute thermal metrics from “wild” melt pools that produce vagueness in the travel direction in each image. To minimize the ambiguity of the travel direction, the known geometry of the L-shaped part leaves only four possible directions that the melt pool can be assumed to travel. In relation to the orientation of the coaxial camera, the melt pool can only travel in the +X, -X, +Y, and -Y directions. This assumes that travel around the corners of the build is ignored. Figure 2.12 portrays these melt pool directions for the L-shaped part. The +Y and -Y directions represent melt pools seen on the 1-bead wide deposition while the +X and -X directions represent melt pools seen on the 3-bead wide deposition.
Additionally without known melt pool location, direction determination can be resolved through analysis of longitudinal temperature profile versus transverse temperature profile. For each coaxial image, the pixel indices with the maximum temperature are stored and set as the location of the center of the melt pool. The location of the melt pool center is consistently in the same 50 by 50 pixel area over the entire coaxial data set, and this melt pool center can be used as the origin to determine the melt pool direction. Thermal gradients in all four directions at the solidus to liquidus region can

Fig. 2.12. Possible melt pool directions
be determined and compared against one another to conclude the location of the trailing edge of the melt pool and hence conclude the travel direction of the melt pool. The validation of the melt pool direction determination is shown through the longitudinal and transverse temperature profiles shown in Figure 2.13 while pixel indices from the melt pool center define the longitudinal and transverse locations across the image. For example as seen with the longitudinal and transverse temperature profile lines, movement in the -X direction is verified by the temperature profiles exhibited in Figure 2.14. The melt pool is moving in the -X direction and the corresponding longitudinal temperature profile shows a skewed distribution in the -X direction. The transverse temperature profile is symmetric through the center of the melt pool. In regards to extracting thermal metrics at the trailing edge of the melt pool, the entire solidus to liquidus region must be visible in the coaxial image to acquire metrics over the course of the entire build. If the full melt pool is not visible, the respective coaxial image is meaningless and the expected thermal metrics are unattainable.
Fig. 2.13. Coaxial image with temperature profile lines of the melt pool moving in -X direction.

Fig. 2.14. Melt pool temperature profiles in the (a) longitudinal and (b) transverse directions for the melt pool moving in -X direction.
2.3.2 Steady State and Transient Movement

In the deposited L-shaped builds, the melt pool oscillates from steady state conditions to transient conditions depending on the physical three dimensional location within the build. The melt pool is in a transient condition during any situation of the build in which the laser head is near an edge or is changing directions. This includes moving from the 1-bead leg to the 3-bead leg, moving between the 3 hatches on the 3-bead wide leg, and reversing direction to begin the next layer. The melt pool is in a steady state condition during the linear segments of the build between laser head direction changes that essentially form the two 2.54 cm legs of the “L”. Coaxial images of a steady condition are shown in Figure 2.15 in which the melt pool is moving in the -X direction. Coaxial images of a transient condition is shown in Figure 2.16 in which the melt pool transitions from around the elbow of the build from the three pass wall to the one pass wall. This transition is from hatch 7 to hatch 8 of the build.

Fig. 2.15. Steady state melt pool across 3 pass wall.
The oscillation of the melt pool conditions contributes to varying thermal metrics across the solidus to liquidus region, across the differing legs of the L-shaped build, and across varying heights of the build.

### 2.4 Coaxial Images of Individual Layers

The following section illustrates individual, consecutive layers of the two builds during initial, middle, and final portions of image acquisition and material deposition. With automation between the three dimensional location of the laser head and the coaxial images, a visual understanding of the melt pool effects can be drawn from the individual layers shown in Figure 2.17 to Figure 2.28 based on physical location in the build. The main aspect that can be derived is the melt pool size and shape. Further analysis of thermal metrics is shown in Chapter 4.
2.4.1 Zero Second Delay

Figure 2.17 to Figure 2.22 portray coaxial images of the individual layers for the 0 s delay build. For a 5 Hz sampling frequency, each of the eight hatches of the 0 s delay build consist of 6-8 thermal images. An additional variable that plays into the 0 s delay is that the back right nozzle of the LENS system became clogged. The melt pools moving in the -X direction are visibly larger than the melt pools moving in the +X direction. This observation may be caused by the clogged nozzle that was corrected for the deposition of the 4 s delay build. During the initial portion of the build shown in Figure 2.17 and Figure 2.18, the melt pools are forming on a cold substrate and the small size of the melt pool of the 3 pass wall indicates this initial formation when compared against the melt pool sizes shown in subsequent layers.

Further comparisons can be made between the middle and ends of each leg as well as between the one pass leg against the three pass leg. The expected trend in the melt pool size during a single hatch is to see smaller melt pools during the steady state regions of the hatch and larger melt pools toward the transient regions of the hatch due to immediate reheating and reduced conduction path throughout the material. This affect is visible for example across hatch 4 of Figure 2.17. Comparing strictly the melt pool size between the two portions of the L, a consistently larger melt pool appears on the one pass leg compared to smaller, changing melt pool size appearing on the three pass. This is due to the one pass leg having a power level of 450 W and the three pass leg having a power level of 350 W.
The last feature of the melt pool to notice for the 0 s delay build is the geometry of the melt pool at the elbow of the build. The transient melt pools at the elbow produce a solidus to liquidus region at the trailing edge of the melt pool that is not directly in line with the X axis or Y axis directions of the standard melt pool movement for this particular build. Figures 2.17, Figure 2.18, and Figure 2.19 display transient melt pools at the elbow of the build.
Fig. 2.17. Hatches 1-4 for the initial portion of the 0 s delay build.
Fig. 2.18. Hatches 5-8 for the initial portion of the 0 s delay build.
Fig. 2.19. Hatches 1-4 for the middle portion of the 0 s delay build.
Fig. 2.20. Hatches 5-8 for the middle portion of the 0 s delay build.
Fig. 2.21. Hatches 1-4 for the final portion of the 0 s delay build.
Fig. 2.22. Hatches 5-8 for the final portion of the 0 s delay build.
2.4.2 Four Second Delay

Figure 2.23 to Figure 2.28 portray coaxial images of the individual layers for the 4 s delay build. For a 2 Hz sampling frequency, each of the eight hatches of the 4 s delay build consist of 3-5 thermal images. Figure 2.23 and Figure 2.24 illustrate consistent melt pools during the initial portion of the build. As the build progresses to the middle and final portions, the melt pool becomes larger with more drastic changes with melt pools reaching outside the coaxial field of view. Once the consistent melt pools are lost from the initial passes, the center pass of the 3 pass wall exhibits a larger melt pool than the outer passes of the 3 pass wall. Figure 2.27 shows a divergence from the expected melt pool geometry and size as the melt pool size oscillates during hatch 3 of the build. With so few melt pools acquired during each of the eight hatches, the changes in melt pool size between transient regions and steady state regions is less apparent than in the 0 s delay build. Once again, the difference in the melt pool size between legs is due to the one pass leg having a power level of 450 W and the three pass leg having a power level of 350 W.
Fig. 2.23. Hatches 1-4 for the initial portion of the 4 s second delay build.
Fig. 2.24. Hatches 5-8 for the initial portion of the 4 s delay build.
Fig. 2.25. Hatches 1-4 for the middle portion of the 4 s delay build.
Fig. 2.26. Hatches 5-8 for the middle portion of the 4 s delay build.
(a) Coaxial image progression

(b) Coaxial image location

Fig. 2.27. Hatches 1-4 for the final portion of the 4 s delay build.
Fig. 2.28. Hatches 5-8 for the final portion of the 4 s delay build.
Chapter 3

Overview of Thermal Metrics

This chapter describes development of the extraction methods of thermal metrics that include thermal gradient, maximum temperature, melt pool pixel area, and length-to-width ratio. The thermal images are two dimensional matrices with the same dimensions as the number of pixels in the original image. From the ThermaViz® system, the matrix size is 480 by 752 entries.

3.1 Thermal Gradient

The thermal gradient across the solidus to liquidus is written as:

\[ | \nabla T | = \frac{\partial T}{\partial (x, y)} \approx \frac{T_S - T_L}{\Delta(x, y)} \]  

(3.1)

where \( \partial T \) is the change in temperature, \( T_S \) is the solidus temperature at 1620 °C, \( T_L \) is the liquidus temperature at 1654 °C, and \( \Delta(x, y) \) is the change in the pixel index across the solidus to liquidus region. The interest of this thermal metric is especially significant in the solidus to liquidus region in representing the portion of the melt pool that borders solidification.
In each of the coaxial thermal images, the thermal gradient is extracted from the number of pixels that lie between the solidus and liquidus temperatures at the trailing edge of the melt pool in line with the melt pool center index. With the pixel to distance calibration of 5.25 µm, the thermal gradient is possible to determine. If the melt pool is moving along the X axis of direction, the thermal gradient is calculated across the rows of the image. If the melt pool is moving along the Y axis of direction, the thermal gradient is calculated across the columns of the image. In addition to the filtering previously mentioned in Chapter 2, further filtering has been implemented to calculate thermal gradient and length to width ratio. Since the coaxial images have imperfect solidus to liquidus regions, data spikes arise in thermal gradient extraction when only using one row or one column for the calculation. To eliminate spikes in the thermal gradient calculation, the values of 25 pixels above and 25 pixels below the melt pool center index are averaged. This accounts for a 51 pixel average which is 10.625% across the 480 pixel height and 6.782% across the 752 pixel width covering a distance of 131.25 µm. The thermal gradient averaging is depicted in Figure 3.1 by the opaque area in the solidus to liquidus region.
3.2 Maximum Temperature

The maximum temperature of the melt pool is obtained by taking the pixel or pixels in the matrix that have the highest value. Figure 3.1 shows five blue pixels that represent a shared value for the maximum temperature for this specific coaxial image. The average row and column indices are used to determine the location of the center of the melt pool. The maximum temperature also establishes the longitudinal and transverse centerlines of the melt pool.
3.3 Melt Pool Pixel Area

The number of pixels inside the melt pool is proportional to the area of the melt pool. For the coaxial images, the solidus to liquidus region ranging between 1620 °C and 1654 °C defined the boundary of the melt pool. In turn, the melt pool pixel area can be determined by the number of pixels above the outer rim of the solidus to liquidus region at 1620 °C. The term “melt pool pixel area” in this thesis is defined as the ratio of pixels that are above 1620 °C to the maximum number of pixels in each coaxial image which amounts to 360,960 pixels. This metric is designated this way due to melt pools that have minor portions of the pool out of the field of view. In turn, several melt pools have portions of visible solidus to liquidus regions in all directions while having pixels that cannot be viewed and included into the true melt pool pixel area.

3.4 Length-to-Width Ratio

The length-to-width ratio delivers characteristics of the melt pool geometry. The ideal geometry of weld heat sources is a double ellipsoid according to the Goldak model [33]. The length-to-width ratio seen in specific legs of thermal videos portrays a geometry that differs quite far from the expected double ellipsoid. Similar to the extraction of the thermal gradient, the length-to-width ratio is obtained by implementing a 51 pixel average for the length and the width along the longitudinal and transverse centerlines. Figure 3.2 shows such centerlines with the direction of melt pool travel.
Fig. 3.2. Length-to-width ratio representation.
Chapter 4

Results

This chapter describes development of thermal metrics extracted from both the 0 s delay and 4 s delay build oriented based on three dimensional location in the build. The thermal metrics described in Chapter 3 are analyzed in isometric view for comparison of separate legs of the L-shaped build, in a straight-on view for understanding of thermal metric changes as the build progresses, and across separate hatches of the three pass wall to examine thermal history effects. The metrics are also arranged for cross sectioning purposes to be analyzed with material microstructure. Variables that alter melt pool characteristics for the L-shaped builds are discussed.

4.1 3D Thermal Metric Maps

The three dimensional thermal metric maps display changes corresponding to the melt pool as well as thermal history throughout the build. Thermal metric values can be attained from the physical locations, averaged over a three dimensional region of the build, and correlated to microstructural features governed by thermal cycling such as α lath width.
4.1.1 Isometric Representation

The isometric view enables comparisons between the 1-bead wide leg and the 3-bead wide leg. Figure 4.1 and Figure 4.2 display the thermal metrics for the 0 s delay and the 4 s delay builds, respectively. Visible thermal metric differences can be seen for each thermal metric across the separate legs of both builds.

The thermal gradient shown in Figure 4.1(a) and Figure 4.2(a) display higher values of thermal gradient on the 1-bead wide than the 3-bead wide. Additionally, the thermal gradient shows vast increases at the edges of each leg and at the elbow of the build compared to the center of each of the legs. This shows a difference of transient melt pools opposed to regions of steady state melt pools, respectively. The thermal gradient on the 1-bead wide leg shows the loss of data for hatch 1 since the solidus to liquidus region is beyond the field of view. Length-to-width ratio displays the opposite effect between the two legs. The melt pool has a lower length-to-width ratio on the 1-bead wide leg than on the 3-bead wide leg in Figure 4.1(b) and Figure 4.2(b). Melt pool pixel area and maximum temperature show a direct relationship to one another. As the maximum temperature of the melt pool increases, the area of the melt pool increases as well. The maximum temperature of the melt pool shown in Figure 4.1(c) and Figure 4.2(c) demonstrate a higher maximum temperature on the 1-bead wide leg than on the 3-bead wide leg. The melt pool pixel area is found in Figure 4.1(d) and Figure 4.2(d).
Fig. 4.1. Zero second delay isometric 3D map.
(a) Thermal Gradient  (b) Length-to-Width Ratio

(c) Maximum Temperature  (d) Melt Pool Pixel Area

Fig. 4.2. Four second delay isometric 3D map.
4.1.2 Individual Wall Straight-On Representation

The straight-on views portray the individual walls of the L-shaped builds for analysis across the height and width. The thermal gradient in the 0 s build sees the highest values at the initial portion of the build and at the right edge of the three pass wall in Figure 4.3. The one pass wall decreases in thermal gradient as successive layers are added to the build. The three pass wall sees similar thermal gradients as the one pass wall initially and then increases as the build height increases.

![Thermal gradient of 0 s delay for (a) one bead wide and (b) three bead wide legs](image)

Fig. 4.3. Thermal gradient of 0 s delay for (a) one bead wide and (b) three bead wide legs
In Figure 4.4, the length-to-width ratio is consistently just below 1 for the entire one pass leg. This may be attributed to molten material of the melt pool flowing to the sides of the 1 bead wide wall. The length-to-width ratio of the three pass leg varies from 0.9 to 1.6. This is representative of the violently changing melt pool geometry during coaxial movement in the +X direction and -X direction.

![Fig. 4.4. Length-to-width ratio of 0 s delay for (a) one bead wide and (b) three bead wide legs](image)
The maximum temperatures presented in Figure 4.5 show temperatures above melting and moving toward a steady state temperature as the build continues. The maximum temperatures at the transient regions of the build see much higher temperatures than the steady state regions due to the fact of heating and immediate reheating in adjacent sections of the L as well as due to a reduced amount of adjacent material for thermal conduction at the edge. This effect is especially visible at the left-most and right-most edges of the three pass wall in Figure 4.5(b).

Fig. 4.5. Maximum temperature of 0 s delay for (a) one bead wide and (b) three bead wide legs
The melt pool pixel area in Figure 4.6 exhibits behavior similar to the maximum temperature regarding dependency upon location within the build. The melt pool pixel area is larger on the one pass wall than the three pass wall due to the increase in power on the one pass wall and is larger during the transient locations of the three pass wall due to immediate reheating. Additionally, the melt pool pixel area generally increases from the start to the end of the build as shown on the three pass wall since deposition starts on a cool substrate and successive passes are being deposited on the previous, hot layer.
Fig. 4.6. Melt pool pixel area of 0 s delay for (a) one bead wide and (b) three bead wide legs

The 4 s delay build expresses similar thermal gradient behavior as the 0 s delay build. Figure 4.7 indicates a thinner solidus to liquidus region at the elbows and turns of the L due to physical temperature effects and due to the methodology for extracting data from the coaxial images. The thermal gradient differs on the three pass wall in the sense that the metric oscillates across the width of the wall. The thermal gradient is higher during the left-most transient section while decreasing as the melt pool begins to reach steady state and then again increases at the center of the three pass wall. The
effect is symmetrical out from the center of the three pass wall. On the one pass wall, the thermal gradient has a sharp increase at the edge of the wall due to the lack of material that is adjacent to conduct heat away.

![Thermal Gradient Diagrams](image)

Fig. 4.7. Thermal gradient of 4 s delay for (a) one bead wide and (b) three bead wide legs

Figure 4.8 shows the length-to-width ratio for the 4 s delay build. The one pass wall indicates that the melt pool transitions from the elbow with a ratio that is 1.15 and
moves to a ratio of less than 1 during steady state due to the melt pool flowing to the
sides of the 1-bead wide wall. The three pass wall does not show the same consistent
d geometry that is seen for the steady state region of the one pass wall. The length-to-
width ratio ranges from 0.8 to 1.6 in the three pass wall after the initial layers in which
the melt pool geometry is consistently at a ratio of 1.1. This can be due to an uneven
surface with prior depositions from lower layers and adjacent hatches. Additionally, the
length-to-width ratio at the right-most edge of the one pass wall is higher due to the
heat being transferred from the three pass wall and in turn elongating the length of the
melt pool.
Fig. 4.8. Length-to-width ratio of 4 s delay for (a) one bead wide and (b) three bead wide legs

The maximum temperatures in Figure 4.9 of the 4 s delay build display the same behavior as the 0 s delay build. The maximum temperatures of the one pass wall reach considerably higher values, the transient portions of the three pass wall have higher temperatures due to immediate reheating, and the temperatures level out to a steady state temperature after lower temperatures from the first initial passes. The only difference that is portrayed are lower temperatures recorded on the left edge of the one
pass wall. This decrease in temperatures is also visible with the melt pool pixel area in Figure 4.10.

![Fig. 4.9. Maximum temperature of 4 s delay for (a) one bead wide and (b) three bead wide legs](image)

The relationship between the maximum temperature and melt pool pixel area is consistent for both builds. The decrease at the left-most edge of the one pass wall is due to the 4 s delay occurring at the ends of each pass and the melt pool in turn reforming
after the pause. The same behavior continues as the maximum temperature for the locations across the steady state and transient sections of the L.

Fig. 4.10. Melt pool pixel area of 4 s delay for (a) one bead wide and (b) three bead wide legs
4.1.3 Three Hatch Split Representation

An interesting component of the L-shaped builds is the three pass wall and the complex thermal histories that are associated when depositing a hatch of the build that is being heated from the adjacent hatches and previous lower layers. Figure 4.11 to Figure 4.14 represent the separate thermal metrics for the 0 s delay build split between the three hatches of the three leg wall corresponding to hatches 2 and 7, hatches 3 and 6, and hatches 4 and 5. Figure 4.15 to Figure 4.18 represent the separate thermal metrics for the 4 s delay build split between the three hatches of three leg wall. Of the four thermal metrics analyzed in this thesis, the only thermal metric that conveys a difference in the build is the thermal gradient in Figure 4.11 and Figure 4.15. The thermal gradient of both builds once again reveals an increase as the melt pool reaches a transient situation. The maximum temperature, the melt pool pixel area, and the length-to-width ratio display uniform scatter in their respective values across the individual hatches of the three leg wall.
(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.11. Thermal gradient for individual hatches of the 0 s delay build.

(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.12. Length-to-width ratio for individual hatches of the 0 s delay build.
Fig. 4.13. Maximum temperature for individual hatches of the 0 s delay build.

Fig. 4.14. Melt pool pixel area for individual hatches of the 0 s delay build.
(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.15. Thermal gradient for individual hatches of the 4 s delay build.

(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.16. Length-to-width ratio for individual hatches of the 4 s delay build.
(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.17. Maximum temperature for individual hatches of the 4 s delay build.

(a) Hatches 2 and 7  
(b) Hatches 3 and 6  
(c) Hatches 4 and 5

Fig. 4.18. Melt pool pixel area for individual hatches of the 4 s delay build.
4.2 Cross Section Analysis Cuts

This portion of the work is applicable to correlation to microstructure. With the three dimensional representation of thermal metrics and the convention of determining material microstructure through cross sectioning, the relationship between thermal metrics to resulting microstructure can be developed. The thermal metrics can be acquired from similar regions in which microstructural analysis from actual builds is performed.

Fig. 4.19. Center third of the three pass wall in red for the (a) 0 s delay and (b) 4 s delay builds
Fig. 4.20. Center third microstructural cut of the 0 s delay.
Fig. 4.21. Center third microstructural cut of the 4 s delay.
4.3 Melt Pool Changes and Effects

The formation, size, and shape of the melt pool are altered by several variables during directed energy deposition. Laser power, laser spot size, laser travel speed, powder size, and powder feed rate alter the melt pool. Other system adjusted variables that reshape the melt pool include the laser and powder alignment (or off-alignment) in the melt pool, the delay time at the end of each pass, the varying power used between the one pass and three pass legs, and the oxygen content in the LENS® chamber during deposition.

Variables also exist that are solely part dependent. The temperature in previously deposited material in lower layers and previously deposited material in adjacent hatches of the 3-bead wide leg are additional factors that reshape the melt pool. The amount of material that is adjacent to deposition accounts for more melting while also playing into the amount of material available to conduct heat away. In conjunction with adjacent material, the melt pool hangs over the sides of the build during each layer and a similar deposition effect occurs during the three pass wall while hatches are overlapping one another.

Geometry of the adjacent material alters the cooling effects of the part. Surface convection changes for the center of the three pass and sides of the three pass. More prominent convective cooling occurs at the edges of the legs especially during delays while shielding gas and powder delivery gas continue to flow. This in turn delivers end effects of transient movement and reforming of the melt pool after pauses.
Lastly, unplanned problems also arise during deposition which produce variables that affect the melt pool. Powder delivery and gas flow rates can be diminished by nozzles clogging during deposition which will affect cooling and thermal gradients.
Chapter 5

Conclusion

An application for thermal metric extraction through data reduction of coaxial thermal images has been developed for representation in three dimensions for correlation to microstructure features. Several image filtering methods have been investigated and applied to the coaxial thermal images for noise reduction and data reduction.

The three dimensional representation of thermal metrics is useful in understanding melt pool characteristics for various locations, heights, and hatches during building of the part. Changes in thermal metrics between separate hatches of the L-shaped parts will influence differences in material microstructure for initial, middle, and final portions of the build as well as the transient and steady state regions of the deposition process. The three dimensional representation allows for thermal metrics to be used to predict microstructure and then material properties for part qualification in a non-destructive method. Cross sectional views of these metrics establish the start of a database of thermal metric values that can be used to correlate to material microstructures. This application bridges the gap between thermal metric evaluation and microstructure prediction which plays an importance in developing “certify as you build” technologies and pointing to use on more complex geometries.
The importance of knowing the direction in which the melt pool is moving and the location of the solidus to liquidus region at the trailing edge of the melt pool has emerged as critical information in thermal metric extraction. Dynamically changing melt pools result in complex analysis in recording and calculating thermal metrics accurately. Extraction of thermal metrics for process monitoring and control must account for changing build geometry and deposition path. More complex build geometries and path plans will result in increased complexity in analyzing the melt pool geometry and solidus to liquidus regions and relating to microstructure. Suggestions for subsequent advancements in this area of research are laid out in Chapter 6.
Chapter 6

Recommendations for Improvements and Future Work

The application of data reduction of large thermal image data sets and the 3D spatial representation of thermal metrics has given understanding to the dynamic changes of the melt pool. Several additional areas need to be investigated in order to extract globally useful information that can be correlated to microstructure used for real-time control.

Furthermore, an expanded filtering analysis of the coaxial image is recommended to determine the precise amount of filtering for calculating useful thermal metrics. Additionally, recording rates above 5 Hz are recommended to enable more complete data sets for improved analysis and to display expanded instances of melt pool changes.

For direction determination, it is important to know where the trailing edge of melt pool is during deposition in respect to the overall location of the build and past thermal history. Post processing of the data makes knowing where the melt pool is and where it is going quite simple. However, to know the entire preplanned path and thermal history does not take into account problems that may arise during deposition and in turn alter microstructure. A direction determination link between real-time three dimensional
locations and solidus to liquidus thickness would allow for advanced calculations at transient regions. This could be implemented through storage of an instantaneous velocity vector with each thermal image to reduce the ambiguity of the melt pool motion.

Implementation of side view thermal imaging system linked with the coaxial thermal imaging system at consistent acquisition times can produce a three dimensional view of temperatures below the surface at regions that strongly affect microstructure development and are known to be influences by subsequent processing. Additionally, the side view thermal imaging system is positioned in a single reference frame while the coaxial imaging system has a moving reference frame. The stationary reference frame allows for extraction of simpler thermal metrics with progression of time. The side view camera also gains access into knowledge of thermal cycling into the previous layers and in turn additional thermal metrics that cannot be viewed with solely the coaxial camera.

Additional experiments are valuable that change only a single melt pool dependent variable while holding other melt pool variables constant can begin to determine what is truly changing the melt pool and solidus to liquidus region. Consistent sampling frequencies for the 0 s and 4 s delay builds would allow for direct comparison of how pauses affect thermal metrics. A direct correlation to experimental microstructure data would be more feasible with consistent sampling frequencies of the coaxial image acquisition.

Lastly, alongside microstructural prediction, the experimental thermal imaging data can be used for model validation in the future.
Appendix A

DMC Code of 0 s Delay Build

REM L-SHAPED BUILD FOR STRATONICS
REM TI64 DEPOSITES AT 500 W AND 25 IPM
REM ********PROCESS PARAMETERS********
REM Layer Thickness = 0.007
REM Hatch Spacing = 0.037
REM Resolution = 5000
REM Contour Feedrate = 20
REM X Axis Resolution = 200000
REM Y Axis Resolution = 200000
REM Z Axis Resolution = 200000
REM Laser On Feedrate = 20
REM Laser On Accel = 40000
REM Laser On Decel = 40000
REM Laser On Shutter Delay = 20
REM Laser Off Feedrate = 35
REM Laser Off Accel = 40000
REM Laser Off Decel = 40000
REM Laser Off Shutter Delay = 20
REM **********************************
REM *BEGINNING OF LINES FOR MULTITASKING*
SH X,Y,Z,W
const=200000
REM ******************
#MAIN
SH E,F,G
OFE=0
OFF=0
OFG=0
REM *END LINES FOR MULTITASKING*
WT 10000
DP 0,0,0
XQ #xyzOut,1
RES=200000
REM *DEFINE LAYER THICKNESS IN INCHES*
vDZ=(0.007*RES)
REM *DEFINE HATCH SPACING*
hSpace=(0.032*RES)
REM *DEFINE FIN LENGTH*
lenOne=(1.0*RES)
lenTwo=(1.0*RES)
REM *DEFINE DELAYS BETWEEN LAYERS*
dLOdd=0.02*1000

dLEven=0.02*1000

REM *DEFINE DELAY AROUND CORNER*

dCOdd=0.00*1000*1000

dCEven=0.00

REM *DEFINE NUMBER OF 1/2 NUM OF LAYERS*

layers=143

REM *DEFINE POSITION VARIABLES*

varZ=0;

REM *DEFINE LASER POWER*

OFW=9.60

REM DEFINE MOTION PARAMETERS

AC 2222222,2222222,2222222

DC 2222222,2222222,2222222

SP 133333,133333,133333

VA 2222222

VD 2222222

VS 83333

REM *SET vector time Constant*

VT 0.5

#LOOP

REM *USE COORDINATED MOVE FOR CORNER if DELAY time is ZERO*

IF (dCOdd=0)
VM XY

VP lenOne,0

VP lenOne,lenTwo,

VE

REM *TURN ON THERMAVIZ CAMERA8 (set bit 15) AND WAIT 20 ms*

SB 15

WT 20

REM *TURN ON LASER (set bit 1) AND WAIT 20 ms*

SB 1

WT 20

REM *BEGIN VECTOR MOVE*

BG S

AM S

REM *TURN LASER off AND TURN SIGNAL off THERMAVIZ*

CB 1

REM 'CB 15

WT dCOdd

ELSE

REM *INSERT PAUSE AT CORNER*

VM XY

VP lenOne,0

VE

SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCOdd
VM XY
VP 0,lenTwo
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCOdd
ENDIF
REM BEGIN LINE SEGMENT 3
PR hSpace,0,0
BG XYZ
AM XYZ
OFW=?
VM XY
VP 0,-lenTwo
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dC0dd
REM BEGIN LINE SEGMENT 4
PR hSpace,0,0
BG XYZ
AM XYZ
VM XY
VP 0,lenTwo
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
CB 15
WT 20
WT dL0dd
REM 'AI 13
REM NEXT EVEN LAYER
REM BEGIN LINE SEGMENT 5
PR 0,0,vDZ
BG XYZ
AM XYZ
OFW=?
VM XY
VP 0,-lenTwo
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCEven
REM BEGIN LINE SEGMENT 6
PR ~hSpace,0,0
BG XYZ
AM XYZ
VM XY
VP 0,lenTwo
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCEven
REM BEGIN LINE SEGMENT 7
PR ~hSpace,0,0
BG XYZ
AM XYZ

REM *USE COORDINATED MOVE FOR CORNER*

IF (dC Odd=0)

VM XY

VP 0,-lenTwo

VP -lenOne,-lenTwo

VE

SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
CB 15
WT dCEven

ELSE

REM *INSERT PAUSE AT CORNER*

VM XY

VP 0,-lenTwo

VE

SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCEven
VM XY
VP ~lenOne,0
VE
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
CB 15
WT 20
ENDIF
SB 14
REM MOVE TO NEXT LAYER HEIGHT
PR 0,0,vDZ
BG XYZ
AM XYZ
REM INSERT PAUSES FOR LAYERS
IF (layers>24)
WT dLEven
ENDIF
IF (layers<=24) & (layers>12)
WT dLEven
ENDIF
IF (layers<=12)
WT dLEven
ENDIF
REM 'AI 13
layers=layers-1
CB 14
JP#LOOP,(layers>0)
WT 1000
CB 1
SB 15
OFW=0
WT 1000
HX1
Appendix B

DMC Code of 4 s Delay Build

REM L-SHAPED BUILD FOR STRATONICS
REM Ti64 deposits at 500 W and 25 IPM
REM ********PROCESS PARAMETERS********
REM Layer Thickness = 0.007
REM Hatch Spacing = 0.037
REM Resolution = 5000
REM Contour Feedrate = 20
REM X Axis Resolution = 200000
REM Y Axis Resolution = 200000
REM Z Axis Resolution = 200000
REM Laser On Feedrate = 20
REM Laser On Accel = 40000
REM Laser On Decel = 40000
REM Laser On Shutter Delay = 20
REM Laser Off Feedrate = 35
REM Laser Off Accel = 40000
REM Laser Off Decel = 40000
REM Laser Off Shutter Delay = 20
REM **************************************************
REM *BEGINNING OF LINES FOR MULTITASKING*
SH X,Y,Z,W
const=200000
REM ******************
#MAIN
SH E,F,G
OFE=0
OFF=0
OFG=0
REM *END LINES FOR MULTITASKING*
WT 10000
DP 0,0,0
XQ #xyzOut,1
RES=200000
REM *DEFINE LAYER THICKNESS IN INCHES*
vDZ=(0.007*RES)
REM *DEFINE HATCH SPACING*
hSpace=(0.032*RES)
REM *DEFINE FIN LENGTH*
lenOne=(1.0*RES)
lenTwo=(1.0*RES)
REM *DEFINE DELAYS BETWEEN LAYERS*
dLOdd=0.02*1000

dLEven=0.02*1000

REM *DEFINE DELAY AROUND CORNER*

dCOdd=0.00*1000*1000

dCEven=0.00

REM *DEFINE NUMBER OF 1/2 NUM OF LAYERS*

layers=143

REM *DEFINE POSITION VARIABLES*

varZ=0;

REM *DEFINE LASER POWER*

OFW=9.60

REM DEFINE MOTION PARAMETERS

AC 2222222,2222222,2222222

DC 2222222,2222222,2222222

SP 133333,133333,133333

VA 2222222

VD 2222222

VS 83333

REM *SET vector time Constant*

VT 0.5

#LOOP

REM *USE COORDINATED MOVE FOR CORNER if DELAY time is ZERO*

IF (dCOdd=0)
VM XY

VP lenOne,0

VP lenOne,lenTwo,

VE

REM *TURN ON THERMAVIZ CAMERA8 (set bit 15) AND WAIT 20 ms*

SB 15

SB 14

WT 20

REM *TURN ON LASER (set bit 1) AND WAIT 20 ms*

SB 1

WT 20

REM *BEGIN VECTOR MOVE*

BG S

AM S

REM *TURN LASER off AND TURN SIGNAL off THERMAVIZ*

CB 1

REM 'CB 15

WT dC0dd

CB 14

ELSE

REM *INSERT PAUSE AT CORNER*

VM XY

VP lenOne,0
VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dC0dd
CB 14
VM XY
VP 0,lenTwo
VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15

WT dC0dd

CB 14

ENDIF

REM BEGIN LINE SEGMENT 3

PR hSpace,0,0

BG XYZ

AM XYZ

OFW=?

VM XY

VP 0,-lenTwo

VE

SB 14

SB 15

WT 20

SB 1

WT 20

BG S

AM S

CB 1

REM 'CB 15

WT dC0dd

CB 14
REM BEGIN LINE SEGMENT 4

PR hSpace,0,0

BG XYZ
AM XYZ
VM XY
VP 0,lenTwo

VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
CB 15
WT 20
WT dL0dd
CB 14
REM ’wait 4 seconds on each end
WT 4000
REM ’AI 13
REM NEXT EVEN LAYER
REM BEGIN LINE SEGMENT 5

PR 0,0,vDZ

BG XYZ

AM XYZ

OFW=?

VM XY

VP 0,-lenTwo

VE

SB 14

SB 15

WT 20

SB 1

WT 20

BG S

AM S

CB 1

REM 'CB 15

WT dCEven

CB 14

REM BEGIN LINE SEGMENT 6

PR -hSpace,0,0

BG XYZ

AM XYZ
VM XY
VP 0,lenTwo
VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
REM 'CB 15
WT dCEven
CB 14
REM BEGIN LINE SEGMENT 7
PR -hSpace,0,0
BG XYZ
AM XYZ
REM *USE COORDINATED MOVE FOR CORNER*
IF (dCOdd=0)
VM XY
VP 0,-lenTwo
VP -lenOne,-lenTwo
VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S
CB 1
CB 15
WT dCEven
CB 14
ELSE
REM *INSERT PAUSE AT CORNER*
VM XY
VP 0,-lenTwo
VE
SB 14
SB 15
WT 20
SB 1
WT 20
BG S
AM S

CB 1

REM 'CB 15

WT dCEven

CB 14

VM XY

VP -lenOne,0

VE

SB 14

SB 15

WT 20

SB 1

WT 20

BG S

AM S

CB 1

CB 15

WT 20

CB 14

ENDIF

REM MOVE TO NEXT LAYER HEIGHT

PR 0,0,vDZ

BG XYZ
AM XYZ

REM INSERT PAUSES FOR LAYERS

IF (layers>24)
WT dLEven
ENDIF

IF (layers<=24) & (layers>12)
WT dLEven
ENDIF

IF (layers<=12)
WT dLEven
ENDIF

REM 'wait 4 seconds on each end
WT 4000

REM 'AI 13
layers=layers-1
JP#LOOP,(layers>0)
WT 1000
CB 1
SB 15
OFW=0
WT 1000
HX1
EN
References


