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In Situ Defect Detection Using Three Color Spectroscopy in Laser Powder Bed Additive Manufacturing

Andrew Drieling

Wright State University - Main Campus

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By

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Abstract

Additive Manufacturing (AM) provides a way to create parts that would be extremely difficult or impossible with conventional manufacturing processes. However, AM also introduces defects, which are detrimental to the mechanical performance. These defects are potentially unknown until post-processing inspection and testing, wasting time and resources on an unusable part or initiating unexpected failure. Historically, spectroscopy has successfully been used for in situ monitoring of laser welding, using changing parameters in the generated plume to predict defects. In situ monitoring using a visible spectrometer for fabrication of Alloy 718 on a test bed laser powder bed fusion system is performed. AM defects, such as keyhole porosity and unfused powder, are detected in the sensor output and a physics-based modeling approach is used to predict defect occurrence. Spectroscopy can provide near real-time monitoring, allowing defects to be predicted, and potentially corrected before the completion of the part, saving time and resources.

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1. Additive Manufacturing

Additive manufacturing is the creation of a part by building it up layer by layer. A wide range of materials can be used in additive manufacturing including: plastics, metals, concrete, paper and even certain types of food. There are many different types of additive manufacturing techniques, but they can be sorted into seven main categories: vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and directed energy deposition [1] [2].

Vat photopolymerization uses photopolymer resin that cures when exposed to a specific wavelength of light. The light is directed to cure the resin one layer at a time. Normally, once the part is done, it must have a final curing with UV light to fully harden the resin. One of the advantages of this method is its ability to produce very fine details due to the concentrated area of light used to produce the part.

Material jetting uses a printhead with many small nozzles to dispense material layer by layer. As the name implies, this process is similar to inkjet printing processes. Like vat photopolymerization, material jetting uses photopolymers that cured by UV light to produce the part. Due to the nature of the print process, multi-material printing is easily achieved and can be used to produce prints with multiple materials or soluble supports to ease post processing.

Binder jetting uses a similar process to material jetting but instead of depositing the print material, a binding agent is selectively applied to a powder bed of material. Once the binding agent has been applied, a thin layer of powder is spread over the bed to form the next layer. This process is repeated until the part is complete. This process is typically used for showcase pieces and not functional prototypes, due to reduced mechanical performance.

Material extrusion is most likely what comes to mind when the topic of additive manufacturing, or 3D printing, comes up. This is due to it being the most common form of additive manufacturing and what most hobbyist grade machines are. To build the part up, material is forced through a heated nozzle, melting it. The nozzle is moved around to deposit material where it is needed until the layer is done. By this point the material has cooled and hardened, and the nozzle advances to the next layer. This technique is used for rapid prototyping and can be used to make functional parts.

Powder bed fusion is similar to binder jetting in the fact that there is a powder bed of the material used to construct the part. However, instead of selectively applying a binding agent, energy is selectively put into the powder to fuse it together to form the part. Powder bed fusion has the ability to produce plastic or metal parts depending on the system. It is the most well established process to produce metal additively manufactured parts.

Sheet lamination uses solid sheets of material to form the layers of the part. The sheets can be cut before or after being added to the part. The most common materials are either metal sheets, which are then ultrasonically welded together, or paper, which is bound together with an adhesive. Like the binder jetting process, sheet lamination additive manufacturing is used more towards producing aesthetically pleasing models, not structural parts.

Directed energy deposition is a technique that brings both the material and the energy to the build site. It is best described as using a wire feed welder to build a part using welds, although the material can be in powder form and the energy usually comes from a laser or other directed energy source. A major advantage of this additive manufacturing technique is its ability to repair

existing components due to the use of a four or five axis arm being used to move the print nozzle.

2. Laser Powder Bed Fusion

The additive manufacturing process with a laser powder bed fusion system starts with the fabrication piston, as seen in Figure 1 below, lowering. The distance the fabrication plate lowers controls the layer height. The roller, or powder sweep, will take powder from the powder delivery system and spend it in an even, thin layer over the fabrication plate. Any extra powder will be deposited in a hopper for collection for future builds. Then the laser will be run over powder bed in a predetermined path to melt the powder into the desired shape for that layer. Once that is over, the fabrication plate will lower and the process will repeat until the part is completed. This system can allow for high resolution of parts, around 100 microns.
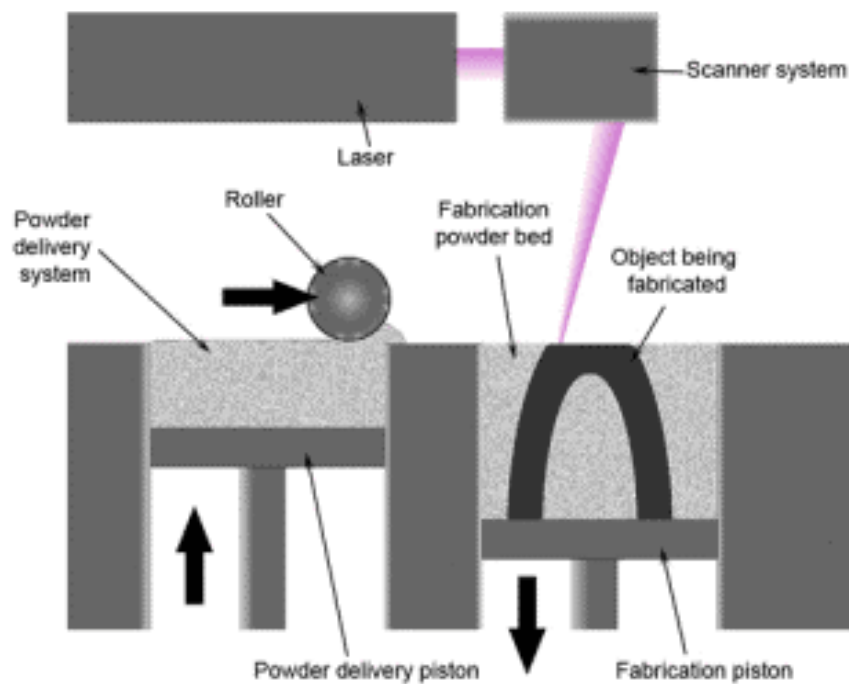
Figure 1: Diagram of laser powder bed fusion system

3. Defects in Laser Powder Bed Additive Manufacturing

According to Grasso *et al*., common defects that occur in metal powder bed fusion processes include porosity, residual stresses, cracking, and delamination, balling, surface deflects, and microstructural inhomogeneities and impurities [8]. The defects range from a wide variety of sources including equipment based, process based, build preparation based, and powder based [8]. Some of these defects can be detected and corrected without using destructive methods during post-processing, while others cannot, rendering the part unusable. Better understanding possible defects and defect sources is one step of many to in-process defect detection and correction.

Porosity, or voids within the part, can be found in one of three locations in an additively manufactured part: within the layer, between two adjacent layers, or on the surface. Porosity greatly impacts the fatigue life and crack growth characteristics of the part, resulting in further investigation on the subject.

Residual stress, cracking and delamination result from the heating and cooling of the part in different locations at different rates. Since the laser provides concentrated heat into the part, small areas of the part will heat up more than their surroundings. Laser scan strategies can also impact this as different scan strategies can concentrate more heat into a small local area of the part longer than others. Material compositions have been found to play a role in this as well. Materials that have large amounts of a secondary element can be affected by different thermal coefficients and expansion rates. Delamination is a special case of cracking where the crack starts and grow in between layers.

Balling is a phenomenon driven by surface tension. It occurs when the molten material in the melt pool forms into balls instead of flattening out over the previous layer. This causes many problems such as internal porosity between the balls, increase in surface roughness, or interference with the recoating system if the balls are large enough.

Geometric defects and dimensional accuracy are exactly what they sound like. This can include part shrinkage, warping, curling and super elevated edges. Other areas affects by this include thin walls, due to the increase in heat input from the reduction of part area. Overhanging surfaces without proper supports also suffer due to the different thermal characteristics of the powder.

Surface roughness has two main contributors: the effect from being manufactured layer by layer, and the actual roughness of the surface. Final surface finish depends on orientation to the build direction. An up-ward surface, downward surface and sideways surface with all have different surface properties. While these can be post processed to improve surface quality, they will still have an influence on fatigue properties.

Due to the high heat and localized inputs for a short time during the powder bed fusion process, the microstructure is significantly affected. Non-uniformity of the microstructure affects the mechanical performance of the part. This can be caused by: impurities, grain size characteristics, and crystallographic textures. Impurities can include unfused powder, surface oxides, and other contaminants. The presence of these impurities affect fracture behavior.

4. Spectroscopy in General

According to the Encyclopædia Britannica, spectroscopy is the "study of the adsorption and emission of light and other radiation by matter, as related to the dependence of these processes on the wavelength of the radiation… spectroscopy is actually a measure of the interaction of photons with matter as a function of the photon energy." [1]. Going to the basics of atoms, every atom has a certain number of electrons in energy levels, dependent on what element it is. These electrons want to be in the lowest energy state possible. However, when excited, they will jump to a higher energy level. The amount of energy required to make an electron jump energy levels corresponds to a specific frequency of electromagnetic radiation when it returns to its lowest state. Every element has a unique set of wavelengths, or spectrum, associated with it, making a spectroscopy a viable means of determining chemical composition.

5. Defects in Laser Welding

The most common defects in laser welding are cracks, porosity, incomplete penetration, undercut, underfill and spatters [2]. Other defects include root sagging, reinforcement, root concavity, and blowouts [3]. D. Y. You *et al.* [2] only lists undercut, blowouts, cracks and spatter as defects that can be detected with spectrometry, the main focus of this research. However, spectrometry has been used to monitor and control penetration depth as well, indicating there are possible applications that extend past their research. This will be discussed in more detail in a later section.

Porosity will easily form in a laser weld that has a deep penetration depth and slow welding speed [4]. Under these conditions, the keyhole is likely to collapse, leaving a liquid wall under the laser. The pressure of evaporation of material from the collapsed wall causes a downward melt flow, potentially leading to pores. When welding speeds are increased, the plume ejects upwards and maintains a stable keyhole to prevent bubble formation.

Incomplete penetration results from not enough energy being put into the weld to achieve the required penetration depth. This can be the result one of two phenomenon. First, the welding speed could be set too high. With this, the laser passes over the weld site too quickly, not allowing enough time for the weld to form at the proper penetration depth. Second, the laser power could be set too low to achieve proper penetration depth. This will not put enough energy into the weld to fulfill the desired parameters.

Undercut and underfill are two defects that are very similar, but occur in different parts of the weld. Both can be defined as a lack of material in the upper weld zone. Undercut is defined as a lack of material in the base metal adjacent to the weld, while underfill occurs in the weld material. In laser welding, there might not be as clear a division since weld material isn't always added during the welding process. However, it is most likely safe to say that undercut is when the edge of the base material is melted away without being replaced, while underfill is a lack of material in the weld itself.

Spatter is the release of molten material from the weld pool. A result of molten material being ejected from the weld site is that undercut, underfill or blowouts can occur in the weld if too much material is lost. Blowouts, or craters, are similar to underfill, however only occur in a small location of the weld rather than along the length of it.

Root sagging and reinforcement are similar in the fact that there is too much material at the weld site. However, root sagging occurs in the lower weld zone and reinforcement occurs in the upper weld zone. Root concavity is similar to underfill in that it is a lack of material, however it occurs in the lower weld zone like root sagging.

6. Monitoring and Closed Loop Control

Research has been done on using spectroscopy for defect detection and closed loop control of laser welding processes. Sibillano *et al.* [5] reported in their article that by monitoring the electron temperature and the correlation between specific spectral lines with spectroscopy, real-time defect detection could be achieve in the laser welding process. To calculate the electron temperature, the application of the Boltzmann plot method and the relative intensity of a selected set of spectral lines were used to provide a simpler calculation that is easy to use in real-time measurements. By conducting some base-line testing using ideal welding parameters, they were

able to determine the expected electron temperature value of an ideal weld and acceptable thresholds such that when values were recorded outside of these thresholds, they could be confident they had record of a defect. Monitoring the correlation between certain spectral lines also detected defects related to the speed of the laser welding process. Variations in welding speed would affect correlation values between different elements present in the process. Different correlation values were analyzed and related to different processing problems or correct processing parameters.

These concepts were used by Sibillano *et al.* [6] and Konuk *et* al. [7] to conduct closed loop control of the penetration depth of laser welding. The electron temperature was calculated using data from the spectrometer and used maintain a predetermined penetration depth. This was possible due to the experimental setup. The collimator used to collect the emission data was directed to record data at a fixed location. This lead to the discovery that the plume generated will shift with the depth of the keyhole. At an increased penetration depth, this caused the collimator to be focused on the weaker, outer shell of the plume, causing decreased values of the electron temperature. Due to the shift in plume location with penetration depth, once the optimal welding parameters are determined, the optimal electron temperature value can be recorded, allowing for closed loop control. Threshold values above and below the optimal value determine the sensitivity of the in-situ monitoring.

7. Motivation

"A one cubic inch LBPF cube is equal to five miles of weld." If defect detection is important in laser welding, where it is only a single pass and the surface of the entire weld can be seen, then it is even more important in laser powder bed fusion where most of the welds are hidden by the top surface. The defects found in laser powder bed fusion are determinately to part performance and current methods to detect defects cannot be employed until fabrication of the part is complete, even then, not all defects can found by nondestructive methods. With current methods, the part must be completely fabricated, then if unacceptable defects are detected, all the time and resources put into that part have been wasted. If the defects go undetected, then they can initiate unexpected failure, leading to potentially dangerous situations. Spectroscopy can provide real-time monitoring of the fabrication process, allowing defect detection and potentially correction, saving time and resources that would be otherwise wasted on useless parts.

8. AM System

The additive manufacturing system used for this project is a custom built laser powder bed fusion system by Universal Technology Corporation. This is an open system, meaning that not only do the sides allow viewing of the process, but it is flexible to allow different sensor setups and more flexible than most systems in regards to controlling build parameters. The system used a 500 watt laser and argon shielding gas. Data is recorded by an array of sensors including

- High speed camera (Phantom V9.1) for high speed visible data
- Profilometer (Keyence laser profilometer) for height measurements of the build
- Visible and Thermal cameras (Basler acA1920-155um) for visible and thermal data
- Spectrometer (PDA36A-Si switchable gain detector) for spectroscopy data
  - Three sensors are run, with 520, 530, and 640 nm filters, one on each

9. Experiment Set-up

The experiment was set up to run 15 individual beads while varying the parameters of speed and power. Three speeds settings were chosen of 500 mm/s, 1000 mm/s and 1500 mm/s. Five power levels where chosen of 150 W, 225 W, 300 W, 375 W, and 450 W. The combination of processing parameters and beam layout can be seen in Figure 2 below.
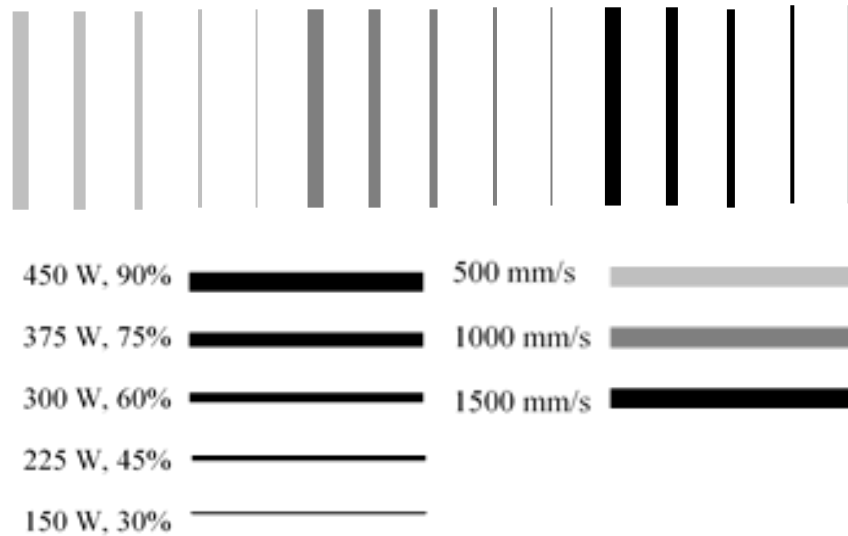

450 W, 90%	500 mm/s
375 W, 75%	1000 mm/s
300 W, 60%	1500 mm/s
225 W, 45%	
150 W, 30%	

Figure 2: Processing parameters and beam layout

10.   Data Processing

Two forms of data were collected for this experiment. First, there was the sensor data from the spectrometer. It outputted data as a table of values. This tables of values was imported into MATLAB where custom code was implemented to sort and plot the data. Second, there was the experiment data, which in this case was the beads themselves. They were looked at under a microscope, where they were photographed and measured.

11.   Results

Once the experiment was complete, the beads were examined under a microscope and accessed for quality. All fifteen beads using different combinations of speed and power can be seen in Figure 3 below. The top set of five were run at 500 mm/s, the middle at 1000 mm/s and the bottom at 1500 mm/s. Within each group, the top bead was run at 450 watts, running down through the power levels to 150 watts for the bottom bead.
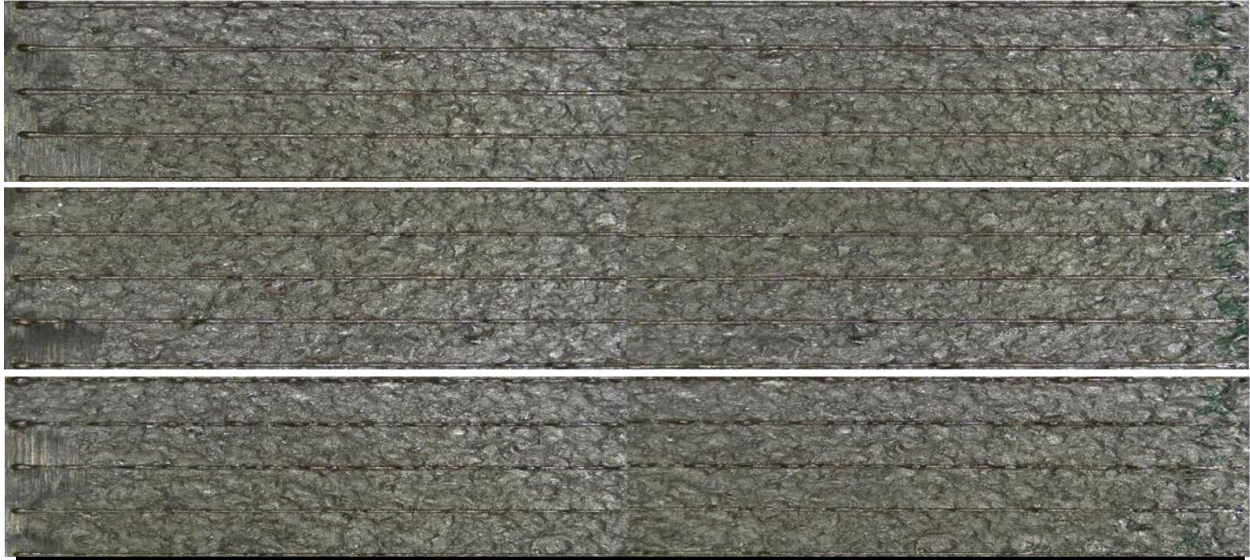
10 mm   *Figure 3: Effects of varying processing parameters on bead quality*

As can be seen from the image above, the effect of varying the processing parameters on the bead quality is evident. The clearest evidence of this can be seen by comparing the 1000 mm/s beads with the 1500 mm/s beads. While the 1000 mm/s bead look fairly consistent across their length, aside from the 150 watt bead, the 1500 mm/s, high power beads show balling across their length. This is demonstrated by the inconsistent bead width.

While the beads were being examined under the microscope, three features were being looked for to conduct further examination upon: keyholing, balling, and highest quality of bead. Keyholing was most prominent in the 500 mm/s, 450 watt "High Power" bead. The 1500 mm/s, 375 watt "Low Power" bead was chosen for balling features. It should be noted that the 1500 mm/s, 430 watt bead exhibited worse balling behavior, however it wasn't able to maintain a continuous bead, therefore it wasn't chosen. The 1000 mm/s, 225 watt "Nominal" bead was chosen for having the highest observable quality in terms of bead width and consistency. These three beads were further examined using the spectroscopy data.

The spectroscopy data for the three beads was pulled from the readings taken with the 640 nm filter, due to that data having the least amount of noise. The three sets of data were plotted on the same plot to compare intensity, namely, average intensity and the intensity range for each bead. The data plot can be seen below in
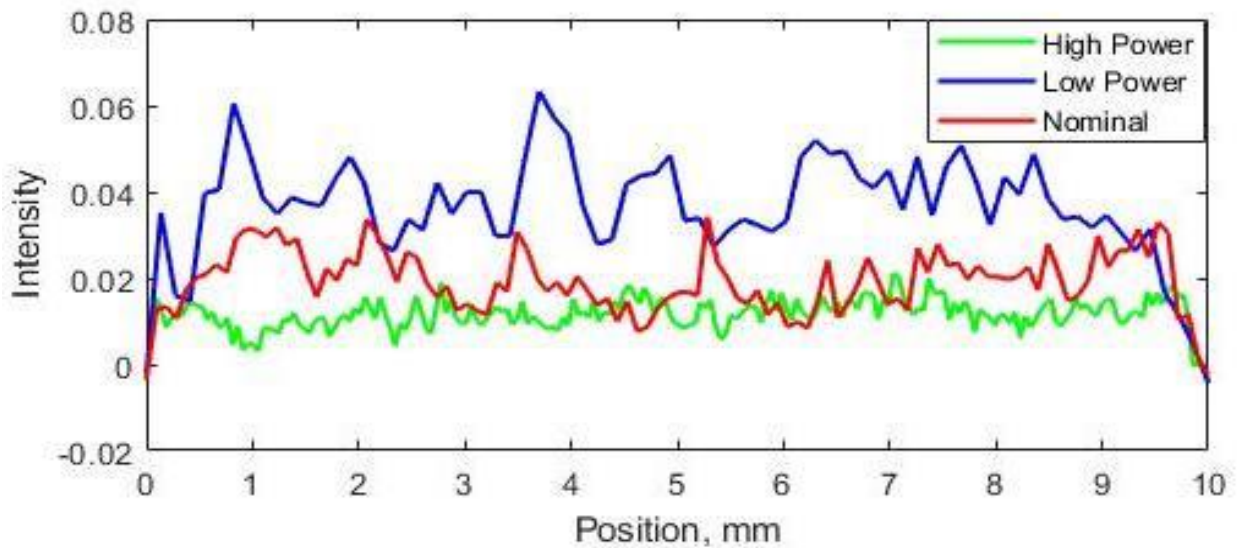
Figure 4: Intensity plot for all three beads of interest

From the plot, it can be seen that intensity values and intensity ranges vary with regards to processing parameters. The low power bead had an average intensity around 0.04 and covered a range totaling about 0.45. The nominal bead had an average intensity around 0.02 and covered a range totaling about 0.25. The high power bead had an average intensity around 0.01 and covered a range totaling about 0.15. A common way to compare energy input being varying speeds and powers is the take the ratio of power to speed. Evaluating this ratio for the three beads, the high power bead had a ratio of 0.9, the low power bead had a ratio of 0.25, and the nominal bead had a ratio of 0.225. It is interesting to note that while the low power and nominal beads had similar ratios, the intensity data plotted for them varied in average value and range, indicating that inputted power is not the only factor changing the intensity data between beads.

Another point of interest from studying the data is the variation in the density of data points between processing parameters. The sensors are collecting data at a fixed rate. Therefore, at the faster build speeds, the bead is completed in less time, meaning less data is collected at it. Comparing the high power data to the low power data, there is a larger quantity of smaller peaks and valleys between the bigger ones than in the low power data. This indicates that there could be missing peaks and valleys in the low power data due to the faster rate at which the bead was constructed.

12.   Conclusions

This project was conducted to determine if spectroscopy could be used to conduct in situ monitoring on laser powder bed additive manufacturing. Research was conducted on laser powder bed fusion processing and defects and compared to laser welding processing and defects. Prior work was found using spectroscopy as a monitoring and control loop for laser welding. An experiment was set up and run to determine if varying the processing parameters had any effect on the spectroscopy data. Varying the processing parameters showed a wide range of defects in the produced beads and analysis of the spectroscopy data revealed that the intensity values varied for the various defects. It was also determined that the energy input is not the only factor varying

the intensity data, as two beads studied had similar energy inputs and different intensity readings. All these results show that closed loop control of laser powder bed fusion is possible with spectroscopy.

13.   Future Work

While some interesting and exciting results were obtained from this project and experiment, it was just the beginning of a longer series meant to further define this area of research. There were many areas of this project that left room to expand upon at a later date. First, instead plotting intensity, the data will be converted to a physical quantity such as temperature or energy. All the beads will be investigated and statistical analysis done on the data, instead of focusing on three beads and pulling observations from the plots themselves. Next, the spectroscopy data will be correlated to the other data collected during the experiment, such as the high speed camera, to determine if areas of interest in the spectroscopy data are also areas of interest in other data sets. In addition to a deeper investigation of the sensor data, the experiment data, in terms of the beads themselves, will be further investigated by sectioning the plate to examine the sub surfaces and cross sections. Physics based modeling will be done to provide a way to make predictions about how processing parameters will affect build quality. Eventually, the build will be expanded to larger geometries, such as cubes or geometries that pose unique problems, such as the transition from a wide cross section to a thin wall.

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