A survey of sensing and control systems for machine and process monitoring of directed-energy, metal-based additive manufacturing

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Abstract

Additive manufacturing of metal parts is, even in the simplest of cases, a complex undertaking. Parts typically involve hundreds or thousands of individual laser or electron-beam deposits, each of which involve a complex interaction between energy source, feedstock, and substrate. During deposition, many of the independent process variables that contribute to overall build quality—such as travel speed, feedstock flow pattern, energy distrbution, gas pressure, etc.—are subject to perturbations from systematic fluctuations (such as changing build geometry or growing global temperature) and random external disturbances (such as spatter on a cover lens). Such process variations affect final part quality, including dimensional tolerance, microstructure, and properties. Researchers have utilized a wide variety of sensor data and analysis for quality monitoring and real-time control of the component geometry, microstructure, and properties. Process attributes that have been targeted for measurement and control include melt pool geometry, temperature, and layer build-height; process parameters that have been utilized for control include processing-head stand-off, substrate angle, travel speed, material feed-rate, and beam power. Here, we survey many of these methods for laser-based, directed-energy deposition, and briefly discuss recently-introduced methods for real-time, closed-loop control of build-plan.

1. Introduction

Today's metals-based additive manufacturing (AM) processes can be considered an evolution of the welding and cladding processes that have been employed for decades. As such, many of the strategies developed for sensing and control of welding and cladding have been or are being adapted for AM. Common examples include single-input-single-output (SISO) control of melt geometry or temperature through variation of laser power or travel speed in order to achieve a consistent weld. More recently, novel sensing and control approaches are being developed to cope with the additional challenges that AM processes bring, including multi-layer deposition with components or features that require complex build paths in each layer. A primary driver of many of these efforts is the need for rapid qualification and verification of low-volume production or specialized AM componets. Here, we survey in-process sensing and control strategies for laser-based, directed-energy AM of metal components and highlight recent developments.

2. AM Processes and Subsystems

Fully-dense metal parts can be built using additive manufacturing processes in one of two categories: (i) directed-energy deposition and (ii) powder-bed fusion (ASTM F42 Committee, 2012). The distinction lies in how material is introduced into the process. In directed-energy systems, powder or wire is fed into a molten pool atop a substrate. In powder-bed systems, a laser or electron beam is scanned over a bed of powder atop the substrate.

Aside from how the feedstock material is introduced, both processes rely on similar subsystems, including: a laser or electron beam, a beam delivery system, motion controls, feedstock delivery system, and environmental controls. The subsystems of both powder-blown and wire-fed directed-energy-deposition processes, along with many of the potential observable or controllable variables, are shown in Figure 1.

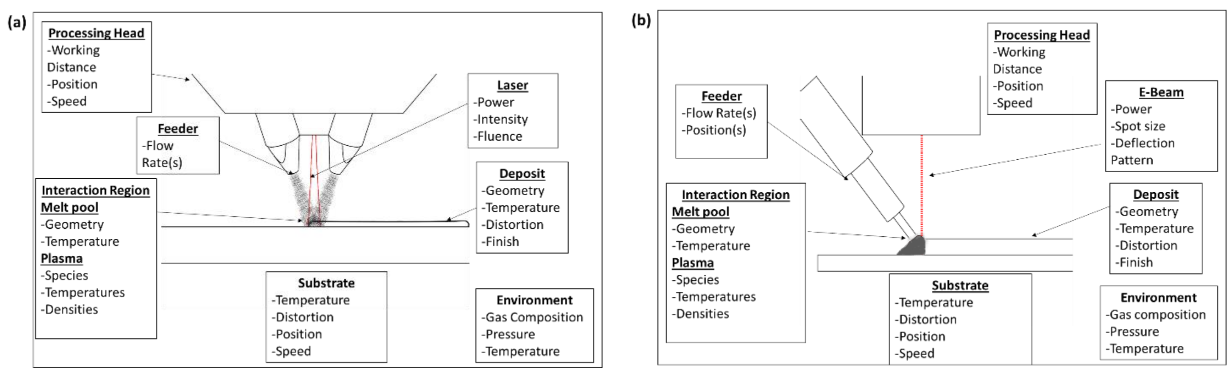

Figure 1: Subsystems of (a) laser-based powder-fed and (b) electron beam, wire-fed directed-energy-deposition processes.

There is potential to employ both sensing and feedback control within each of these subsystems. Here, powder-blown, directed-energy additive manufacturing is dicussed. A high level summary of some of the details of the process, from start to finish, is provided below in order to set the stage for subsequent sensor and control discussions.

A typical laser-based, directed-energy-deposition process begins with positioning of a substrate or build plate in the work space. Since the laser beam optics and powder feed nozzles are designed to focus to a specific location, they will operate best at a predefined, optimal stand-off distance. Variations in the location of the substrate position caused by misalignment, overbuilding, or in-process distortion will result in variations in powder feed alignment or energy density that can impact the process. Powder is typically fed through one or more coaxially-aligned nozzles with assistance from a carrier gas. Variations in powder flow resulting from disturbance in chamber back pressure, powder clogs, or other instabilities will impact the manner in which the laser beam interacts with the feedstock and can lead to melt pool fluctuations and process instability. The laser beam is then delivered to the interation zone through a series of optics. Misalignment of the laser beam or contamination/damage to the beam delivery system will impact energy density at the surface, and can also produce fluctuations in the melt pool. The laser energy interacts with the powder and substrate, melting both. Some vaporization also occurs. Contamination of the powder or substrate can result in release of non-metal gaseous emissions that can result in porosity upon solidification. Volatilizing contaminants or low–vapor-pressure alloy-constituents can also lead to rapid expansion of gas, resulting in undesirable, and sometimes violent, expulsion of liquid metal and/or powder.

The beam-material interation zone is translated in space relative to the substrate and previous depositions. If the volumetric energy transferred to the build is too low for a given initial substrate temperature, due to low laser power or high travel speed, then there is potential for lack of fusion, reduction in deposition volume, and/or reduction in depth of the fusion zone. This can result in a reduction of dilution, or variation in build geometry (height, width, angle of repose) leading to detrimental misalignment in subsequent deposits. If the volumetric energy is too high for a given substrate temperature, then puddle size will increase and overbuilding may occur, or increasing vaporization may lead to a keyholing effect and undesirable melt ejection from the vapor recoil force. As the melt pool solidifies, thermal gradients will lead to residual stresses that can result in substrate distortion. As the build proceeds, the energy that is deposited into the component may lead to a global temperature rise that can influence many of the factors above.

3. Sensing and control of machine variables

During normal operations, all AM systems must operate within known limits that are largely independent of the details of the process: the beam power and mode ought to be stable; motion stages and scanners should to be precise and accurate; material feed rate or powder-layer thickness ought to be well-defined; and, chamber pressure and gas concentrations ought to remain constant during processing. To address this category of process parameters, process monitors and warning indicators, or independent, single-input-single-output (SISO) control loops are typically employed.

3.1 Laser beam delivery

The laser energy reaching the interaction zone can vary during normal operations due to electronic noise within the laser system, variations in beam front due to distortion and variation in the index of refraction resulting from thermal load on the optics, or damage to optical elements from process contaminants. Internal fluctuations in beam power can be reduced though closed-loop control of pump power (Paschotta, 2008). Systems based on monitoring reflections from turning mirrors (Johnstone, 2000) and from laser-induced Rayleigh scatter in air (Ophir Photonics, 2014) have potential to be used for non-intrusive, real-time measurement and assessment of both internal and external laser beam power fluctuations. Thermal load on the optical elements produces changes in lens geometry and index of refraction that lead to energy fluctuations at the substrate. These fluctuations are difficult to actively control, but are only an issue when operating at high laser powers, and effects can be reduced via active cooling.

Optical elements closest to the laser-substrate interaction zone are most vulnerable to be damaged from gaseous process emissions and melt spatter, and are thus most likely to distort or attenuate the laser beam. If contamination is sever, processing with a high-power laser can induce thermal stresses within the lens that result in cracking, as shown in Figure 2. In directed-energy laser deposition systems, a focusing lens, together with a protective cover lens are enclosed within a processing head. Various researchers (Bi et al., 2007; Tönshoff et al., 2003) have shown that monitoring of the reflected laser light from the protective glass using a photodiode can be used to sense damage to the protective cover lens. Additionally, they show that monitoring temperatures within the cladding head can also be used for real-time assessment of the condition of the optics. A schematic of the optics monitoring setup used by Bi *et al.* (Bi et al., 2007) is shown in Figure 3.

Figure 2. Extreme case of optics damage during high power laser processing.

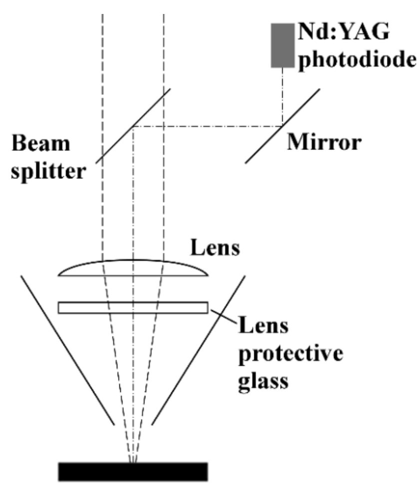

Figure 3: Schematic of an optics system utilized to monitor contamination of beam delivery optics. Adapted from (Bi et al., 2007).

3.2 Chamber environment

Monitoring of key conditions within the processing environment is straightforward. For laser-based processes, the processing chamber is filled and recirculated with argon, nitrogen or other inert gases, depending on the material being deposited, in order to limit contamination through oxidation or other source. To ensure part quality, oxygen concentration within the build environment is typically monitored using a trace oxygen sensor. Electrochemical oxygen sensors can measure concentrations down to parts per million, but require periodic calibration since exposure to oxygen that occurs during normal operations reduces sensor lifetime.

Chamber pressure fluctuations have been observed to influence the feed rate of powder and the flow rate of processing gas in powder-blown systems. Additive manufacturing processes are also vulnerable to contamination from outgassing of polymers or vaporization of water or other volatile compounds.

3.3 Feedstock delivery

To achieve consistent quality, powder-blown and wire-fed directed-energy-deposition systems require a well-defined volume or mass of material feedstock to be introduced at the proper rate to the correct location. In both powder-blown and wire-fed processes, the angle, location (with respect to the beam), velocity and/or mass flow rate at which material is fed, (as well as powder feedstock and flow stream morphology for powder-blown systems), all affect the deposition process. A study of the impact of powder, carrier gas, and nozzle characteristics on powder flow was performed by Balu *et al.* (Balu et al., 2012) to maximize powder concentration at the substrate working distance. Various researchers have demonstrated ways to monitor, and in some cases control, feedstock properties to ensure quality depositions.

In powder-blown systems, powder delivery and flow characteristics must remain consistent if consistent quality is to be achieved. From a practical standpoint, nozzles can clog or suffer damage during operations. Examples of a clogged and damaged nozzles are shown in Figure 4.

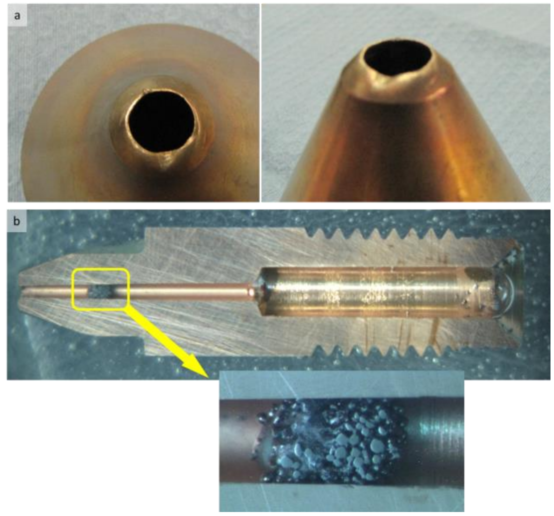

Figure 4. Example of nozzles that were (a) damaged, and (b) clogged during additive manufacturing processes.

To provide real time monitor of perturbations of powder flow resulting from damaged or clogged nozzles, imaging methods to assess flow at the processing head have been developed. One example of such a system, developed by Nassar and Reutzel (Nassar and Reutzel, 2014), uses a filtered camera to view the light from a laser line generator that is reflected off powder exiting the nozzles during the deposition process. Figure 5 illustrates this method, and shows resultant images prior to analysis. Automated identification of clogged or damaged nozzles can be important for quality control during long builds.

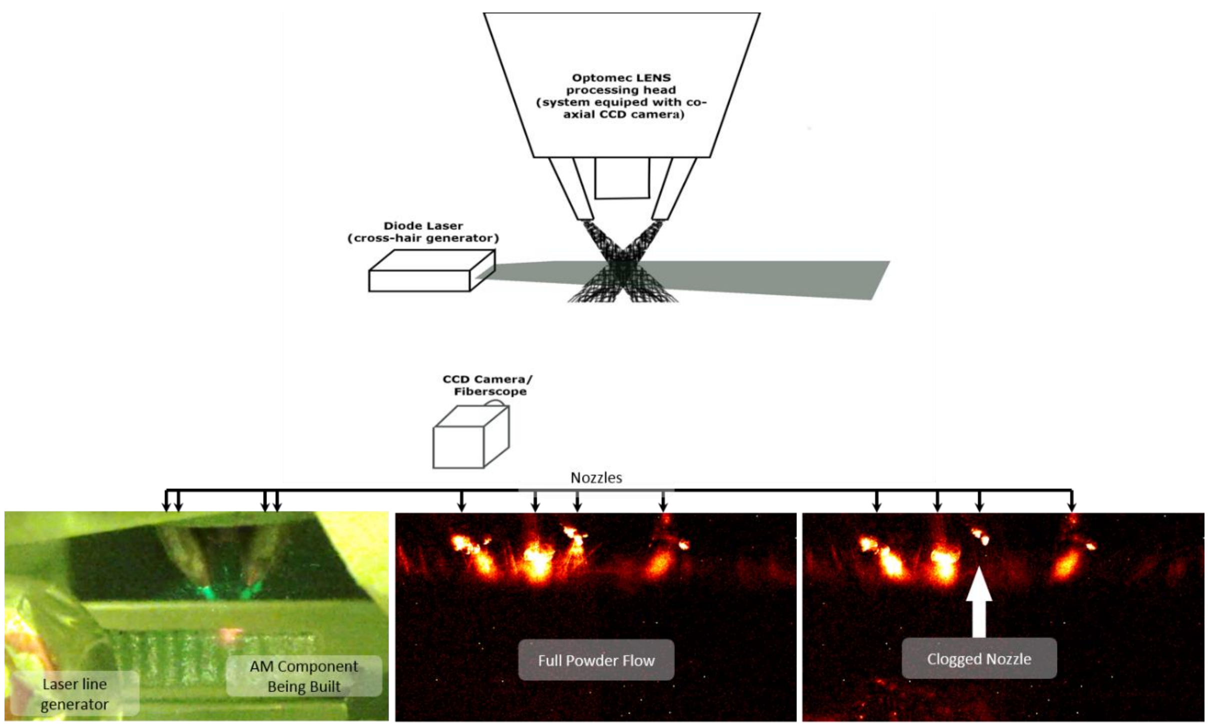

Figure 5. Illustration of method to assess powder flow from individual nozzles.

In powder blown systems, real-time monitoring and control of feed rate is most often achieved using continuous weight measurements. Due to slow sampling rates found in typical commercial weigh-based measurement systems, there is a significant time delay between changes in set point and a stable powder flow. This is especially problematic when more than one powder feeder is used to produce alloys or functionally-graded materials. Hu and Kovacevic (Hu and Kovacevic, 2003) developed a diode-based sensor that measures the attenuation of a laser beam as it is transmitted through a glass tube connected to the powder feeder. The setup is illustrated in Figure 6.

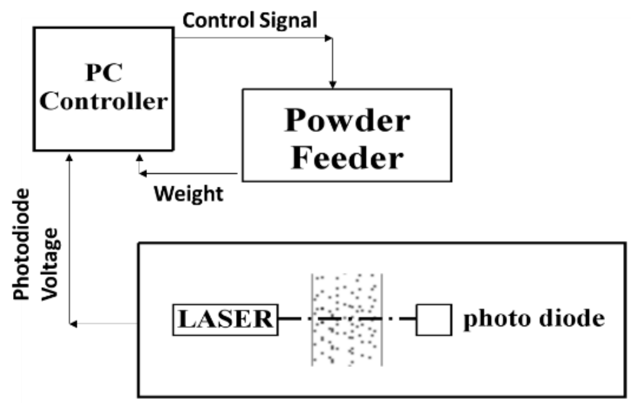

Figure 6: Illustration of the Hu and Kovacevic powder feed rate controller. Adapted from (Hu and Kovacevic, 2003).

An additional delay results from the fact that, in many commercial systems, the processing laser head is located away from the powder feeder, resulting in a substantial lag between changes in set point and observable changes in feed rate at the beam-material interaction zone. This delay time depends on the length of the tubes connecting the feeder to the deposition head coupled with the material feed rate.

To account for this and other delays in powder flow, Muller *et al.* (Muller et al., 2013) developed a model of powder flow rate at the deposition head as a function of the input signal to the powder feeder. They then coupled the model to a closed-loop predictive control system, enabling them to generate an NC program that compensates for delays in order to deposit functionally-graded materials with the desired composition.

While it is difficult to precisely control the material feed-rate in powder-blown processes, it is relatively easy to do so in wire-feed processes. Commercial wire feeders have long existed for the welding industry and can be readily integrated into AM machines. They handle a wide range of wire sizes and typically allow real-time control of feed rate based on an analog voltage or current. One possible source of noise during wire feed operations is slipping of the wire relative to the feed rolls, but this can usually be corrected by reducing the feedlength, eliminating sharp bends in the wire conduit, and by properly adjusting the roller pinching force.

4. Sensing and control of build attributes

While sensing and control of process-independent machine variables can be realized largely without concern for the specifics of the process, process-dependent build attributes require some knowledge of the desired part geometry, material composition, density, microstructure, and other properties. Many of these characteristics cannot be directly measured, e.g. material composition, density, and microstructure. However, certain characteristics of the beam-material interaction, as well as solidified regions of the deposit, can be monitoring to allow estimation of these variables. For example, it has been argued that characteristics of the melt pool geometry can be used to predict deposited microstructures in Ti-6Al-4V (Bontha et al., 2006) and Inconel 718 (Thompson, 2014).

4.1 Melt Pool Geometry

As noted earlier, melt pool geometry is influenced by a wide variety of process conditions. Since it is straightforward to introduce coaxial imaging systems to a laser deposition system, the melt pool is an attractive characteristic of the process to use for monitoring and control. The impact on melt pool due to changes in build geometry, laser power, initial temperature, alignment to adjacent depositions, and many other factors, is illustrated by observing the variation in coaxial thermal melt pool images collected throughout deposition of a single layer of a relatively simply build (Figure 7). Note that the melt pool width increases in a regular fashion as the build proceeds along the first leg, but varies significantly once it enters the 3-bead wide portion of the build. In the past two decades, many researchers have utilized coaxial melt pool imaging to monitor and control the process.

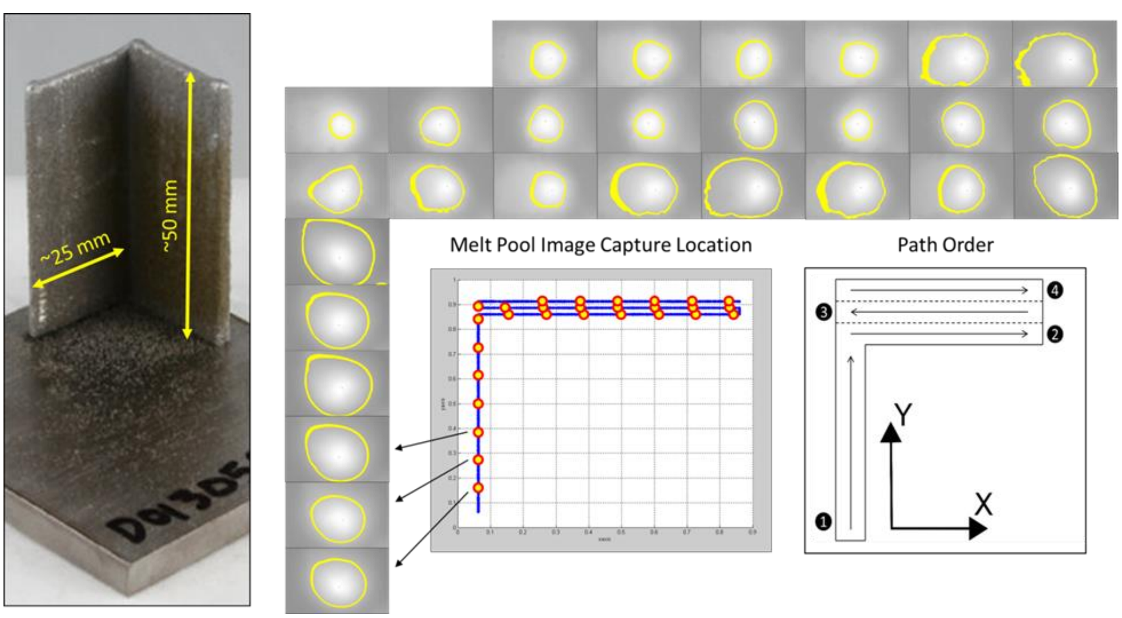

Figure 7. Coaxial thermal images of melt pool collected during a laser-based directed-energy deposition using powder feedstock without feedback control. The yellow portion of the image highlights the liquidus-to-solidus region.

In some of the earliest work in process control related to laser- and powder-based directed-energy-deposition systems, Hofmeister *et al.* (Hofmeister et al., 1999) used a visible light pyrometry technique to determine melt pool characteristics. They noted that the heat sink conditions at each phase of the deposition varied appreciably during a complex build, and had a profound impact on the melt pool size. Images collected with a coxial, filtered high speed video camera were converted to temperature in order to calculated melt pool area. This melt pool area was used as input to a proportional-integral-derivative (PID) controller which varied laser power to maintain constant melt pool area. The controller took in consideration whether a boundary (contour) or fill pass (hatch) was being made. They demonstrated improvement in consistency of build dimensions with the controller.

Several years later, Hu *et al.* (Hu and Kovacevic, 2003) utilized coaxial single-color IR imaging to demonstrate that, for a select group of processing conditions, the melt pool width and area could be correlated to the fusion zone depth and average melt pool temperature. Later, Colodron *et al.* (Colodron et al., 2011) showed that melt pool width also correlated closely to dilution and used an FPGA-based controller to vary laser power to control melt pool width based on measurement with a 50 fps, coaxial CMOS camera. Colleagues followed up a year later (Araujo et al., 2012) with enhancements to compensate for noise in the images resulting from powder, optics contamination, and other effects. This same year, Hofman *et al.* (Hofman et al., 2012) also demonstrated that varying laser power with a melt pool width controller was also effective in maintaining consistent microhardness in the face of substantial local changes in heat sink from geometry effects.

4.2 Melt pool temperature

Melt pool temperature is another characterstic that is impacted by many process variations and that influences final build attributes. In contrast to performing complex data analysis on noisy images, average melt pool temperature can be readiliy measured using low-cost photodiodes or other sensors. Bi *et al.* (Bi et al., 2007, 2006) recognized the potential benefits of such a sensor, and showed that a suitable photodiode could be easiliy integrated into a processing head to provide a coaxial measurement, could identify anomalous build characteristics, and could be correlated to dilution. They also demonstrated melt pool temperature control by varying laser power. More recently, Bi *et al.* (Bi et al., 2013) confirmed that part geometry has a strong influence on melt pool temperature, and investigated the use of changing the energy density by means of laser defocusing to compensate. They found that controllability with these techniques was limited before low irradiance significantly degraded deposition quality. This study also revealed that oxidation during processing changes the spectral emissions and may result in false readings using this technique. Song and Mazumder (Song and Mazumder, 2011) demonstrated melt pool temperature control using measurements from a dual-color pyrometer by varying laser power using a controller based on an experimentally identified state space model of laser power-to-melt pool dynamics.

4.3 Deposition height

An important challenge during additive manufacturing is achieving consistent material characteristics and geometry. In particular, build height is strongly influenced by distortion and changes in powder capture efficiency. Optical sensors are most often used for non-intrusive measurments of build height. The chromatic-aberration-based technique developed by Hand *et al.* (Hand et al., 2000) detects the UV and IR components of the continuum radiation generated during processing. Taking advantage of varitions in intensity of each spectral range with working distance, due to chromatic distortions, they designed a height control system and coupled it with a laser-power controller based on pyrometer measurments of meltpool temeraperaure.

Fathi *et al.* (Fathi et al., 2006) utilized a more-conventional, CCD imaging sensors to assess the influence of various process conditions on deposition height, then utilized system identification techniques to determine a dynamic system model. With this, they were able to construct PID controllers both with and without an additional feedforward term (based on the identified system dynamics). They varied travel speed to control build height and found that inclusion of the feedforward term resulted in responses more closely following the desired set point. More recently, Fathi teamed with Mozaffari (Mozaffari et al., 2013) to develop advanced system identification techniques to develop neural network and other models of the highly nonlinear deposition process. This enabled them to develop a multi-input multi-output (MIMO) controller capable of performing multi-objective optimization. In this case, they were able to demonstrate optimization of both clad height and dilution by varying travel speed, laser power, and powder flow rate.

Song *et al.* (Song et al., 2011) developed a two-input, single-output hybrid control system that employed a master height controller and slave temperature controller. The height was measured with 3 high speed CCD cameras, and the temperature was measured with a 2-color pyrometer. When the melt pool height exceeded a prescribed value, the temperature controller was blocked and laser power was reduced to limit build height. When melt pool height was within the specified range, the laser power was varied to control melt pool temperature. They found that this hybrid approach provided stable builds.

4.4 Optical Emissions

During processing the laser beam heats up the powder and substrate material to elevated temperature leading to melting and vaporization. Bartkowiak (Bartkowiak, 2010) demonstrated that the optical emissions and spectral lines that can be collected from the vapor emissions generated during low power (<2 kW laser) deposition are related to the temperature and composition of the melt pool. Song and Mazumder (Song and Mazumder, 2012) also demonstrated an ability to monitor chromium composition in real time during deposition of H13 tool steel. After proper calibration, they were able to predict chromium composition to within 2.8% atomic weight. Nassar *et al.* (Nassar et al., 2014a) evaluated spectra from optical emissions during a build designed to have intentional lack-of-fusion defects. Their analysis suggests that optical emissions may contain information that can be related to build defects.

4.5 Path Control

Process controller development efforts to date have targetted real time control of one or more build attributes based on the specific charactersitcs of the process that are possible to sense, coupled with the process parameters that are available to vary. They promise to improve build consistency that is currently degraded by systematic process variations that are not compensated with traditional, purely feed-forward processing. However, they all operate independent of the processing path, and do not allow variation in the path that may help to decrease thermal build-up or distortion. Additionally, they do not provide means to correct the inevitable intermittent defects that will occur in production. In contrast to a casting of forging, the layerwise nature of the AM process allows machine access to the interior of the component as it's being built, offering opportunity to correct certain types of defects.

A system architecture has been developed and integrated into a commercial AM system that allows real-time adjustment of the build plan during each layer. The data flow utilized in the architecture is illustrated in Figure 8. To test and demonstrate the architecture, a test case was defined in which the build plan (specifically, the hatch pattern) was modified in real time based on a temperature reading. Prior to executing a given hatch, a pyrometer was used to interrogate the temperature of the substrate. If the substrate temperature exceeded an arbitrary set point, then the hatch was skipped until later, and the next programmed hatch was processed with the same algorithm. After all acceptable hatches were processed, the hatches that had been previously skipped were processed. Figure 9 illustrates the impact of the controller activity on the hatching order. Evaluation of cross sections has revealed that the closed loop controller produces a build with less variation in microstructure than an uncontrolled deposition (Nassar et al., 2014b).

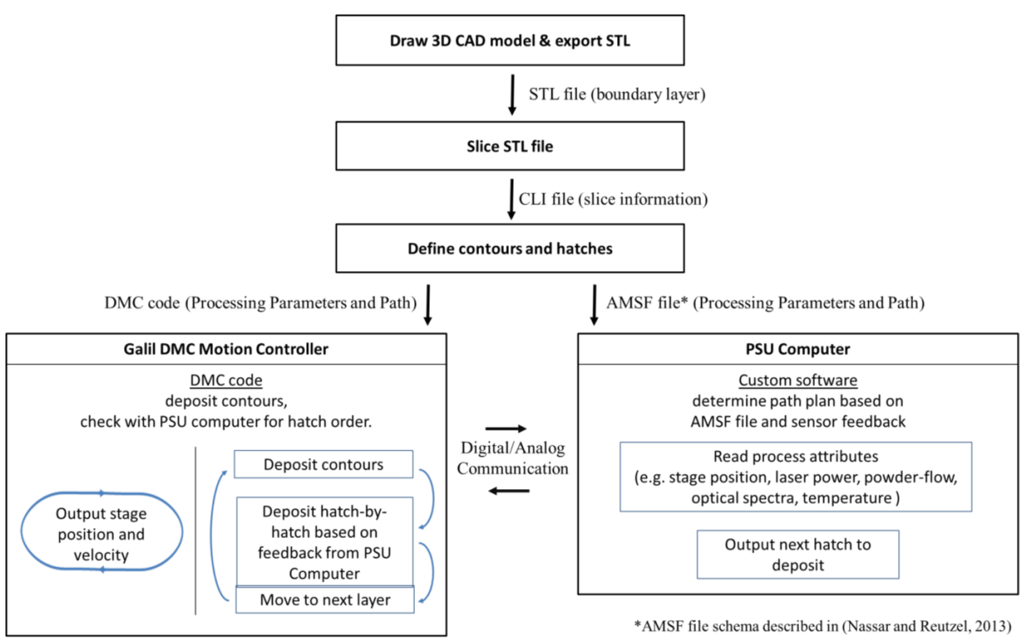

Figure 8. System architecture to enable real time path modification and control.

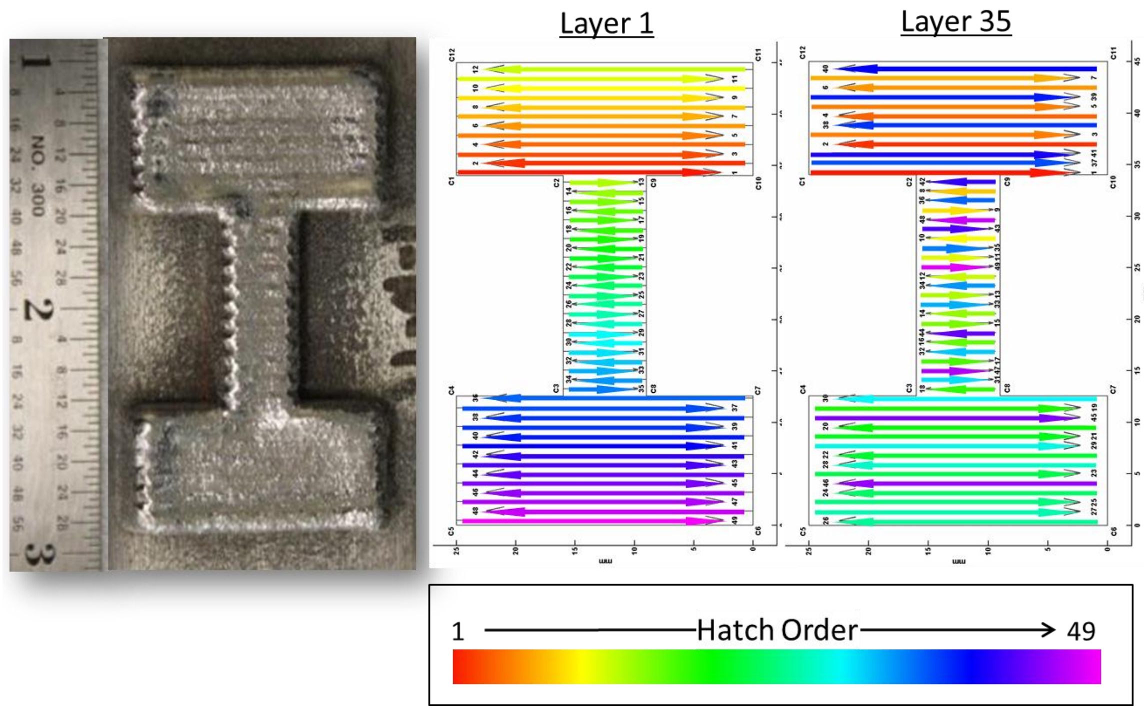

Figure 9. Illustration of changing controller activity in changing hatch order during a build.

5. Conclusions

Without the development of highly automated computer-based controllers for processing and motion, modern additive manufacturing would not be possible. These systems lend themselves to continuing development and integration of machine- and process-based sensing systems that improve process documentation, and enable control of build characteristics and quality. Such developments are essential for qualification activities and to garner widespread acceptance by the technical community. The research community has made numerous advancements in sensor and control technologies that bolster these efforts.

In recent years, researches have developed sensors for monitoring of the laser beam and delivery optics, chamber pressure and oxygen concentration, powder and wire feed rates, melt pool temperature and dynamics, optical emissions, and substrate temperature. A subset of these efforts have been higlighed here along with recent developments towards in-process, path-plan modification. To acheieve the goal of rapid qualification of AM parts, further progress and commercialization of sensors and controls must continue.

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