In-Process Monitoring Techniques for Laser Powder Bed Fusion

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Introduction

As metal additive manufacturing (AM) processes shift from part prototyping to part manufacturing, emphasis is being put on in-process monitoring and control to strengthen the quality control standard for the next generation of commercial AM machines. Maintaining high overall equipment effectiveness with metal AM is particularly dependent on the end quality of the parts coming out of the chamber.

Currently, the level of quality control in most powder bed AM machines is not advanced enough to determine quality throughout the build. Its inadequacies are residual as the quality standard is based on its rapid prototyping predecessor, which optimizes speed and cost savings to gain knowledge on design nuance, as opposed to making part quality paramount. The current quality control methodology is open-loop, relying on fine control of input parameters, but ignoring the potential for noise inputs to wreak havoc on the resultant part quality. For processes that include build times measured in hours, days, and even weeks, ignorance to noise input is a major quality control blunder.

Additive processes provide a unique perspective on quality incompliance as part production is carried out hatch-by-hatch, layer-by-layer. Potential quality issues are not only available for the viewing, but are also accessible for in-process repair. This is a unique advantage over conventional manufacturing processes, and opens the door for first-time quality if methodologies can be developed to take advantage of it.

Part quality for metal AM parts is evaluated on dimensional, volumetric, metallurgical, and surface finish compliance, where each evaluation area makes up a portion of the part quality landscape. No single sensing technique can monitor all aspects of the quality landscape. Each has its own core competencies and natural deficiencies. The challenge is understanding which techniques offer the best performance, and which techniques complement each other. EWI has taken on this challenge by constructing open architecture AM systems for experimentation and execution of research programs focused on in-process monitoring of metal AM processes.

Open Architecture L-PBF Test Bed

The first open architecture metal AM system constructed at EWI is a laser powder bed fusion (L-PBF) system. Commissioned by NIST, this L-PBF test bed provides the means for both evaluating different quality sensing techniques and controlling the process to purposefully implement defect-inducing conditions.[1] Where commercial systems remain relatively closed off to the end user, the L-PBF test bed offers full access to all aspects of the process. The system, shown in Figure 1, provides open access to the monitoring of the process (e.g., beam delivery path, viewing windows, internal sensor mounting, and integration), and open access to control of the process (e.g., path planning, process parameters, and system I/O).

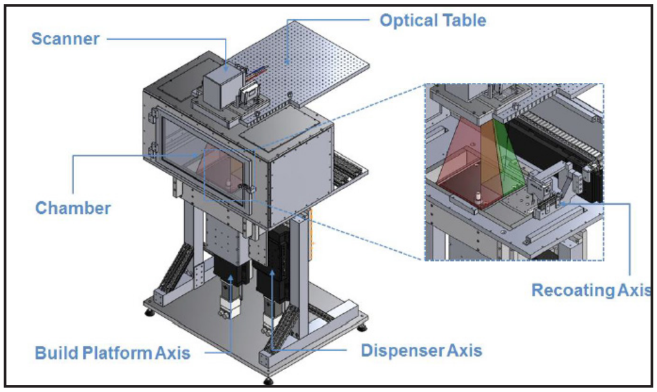

Figure 1: L-PBF test bed schematic.

Sensing Techniques

Several sensing techniques have been integrated and evaluated within the L-PFB test bed. These techniques include local sensing techniques which interrogate the melt pool and acquire data at high rates (e.g., greater than 1000 Hz), and global sensing techniques which interrogate the build area and acquire data on a layer-by-layer basis.

Again, different sensing techniques hold different advantages and disadvantages. Local sensing techniques are true real-time data generators, typically measuring process by-products that may indirectly infer a quality condition. For example, photodetectors and spectrometers measure light intensity and wavelength from the laser plume which have been shown to link to volumetric and metallurgical compliance as shown in Figure 2.[2,3] Thermal melt pool imaging captures infrared by-product from the melt pool and heat-affected zone to produce a calibrated images of the melt pool. Both temperature and spatial melt pool metrics can be linked to process stability and eventual volumetric defect formation (Figure 3).

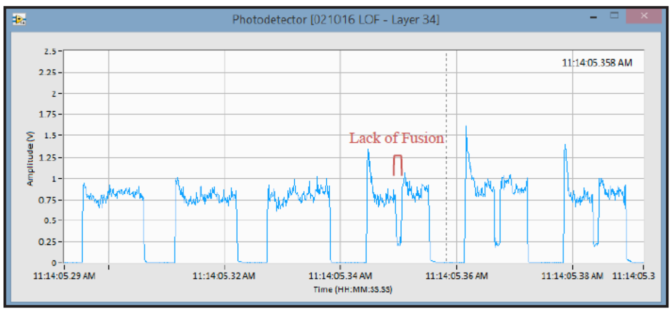

Figure 2: Time-based photodetector signal with lack of fusion indications.[1]

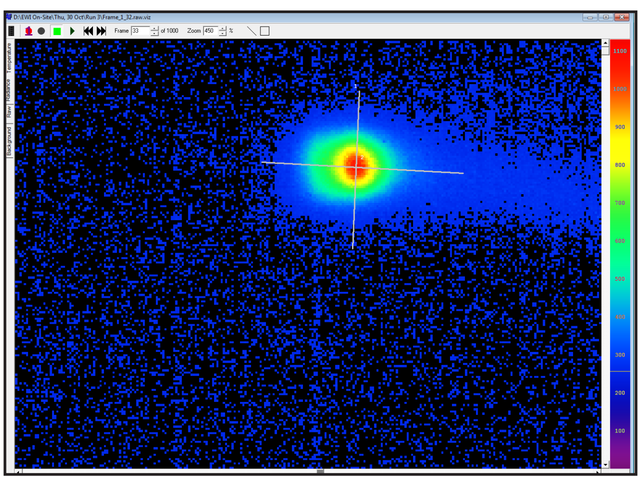

Figure 3: Example thermal melt pool imagery for L-PBF.[1]

Global sensing techniques typically acquire data on a layer-by-layer basis, where the data directly infers a quality condition. For example, visible spectrum build area imaging (e.g., machine vision) captures top view images of the build area before a layer is processed and after a layer is processed. Pre-processing images may identify irregularities in the powder spread (e.g., angled spreading, waviness, troughs from blade damages, etc.) or poor coverage due to part distortion or poor processing on the previous layer. Post-processing images may directly measure geometric compliance and irregular surface conditions. Laser profilometry and three-dimensional structured light macroscopes (Figure 4) produce similar outputs based on the surface topography data they generate. Data can be collected pre-process and post-process and used to directly measure geometric and surface finish compliance. Thermal build area imaging captures top view temperature maps of the build area throughout processing and post-processing to measure heat flow. These measurements in combination with numerical modeling techniques can theoretically be used to predict the metallurgical state as a function of three-dimensional position within the part. Global sensing techniques may also include non-destruction testing methods. For example, eddy current arrays may be attached to the recoating for scanning over the part to measure both surface topography variation and sub-surface cracks and voids as illustrated in Figure 5.[4]

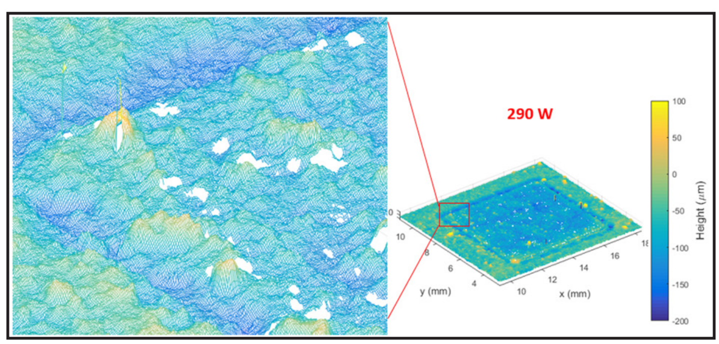

Figure 4: Three-dimensional structured light macroscope data over a 10 × 10 mm² cube.[5]

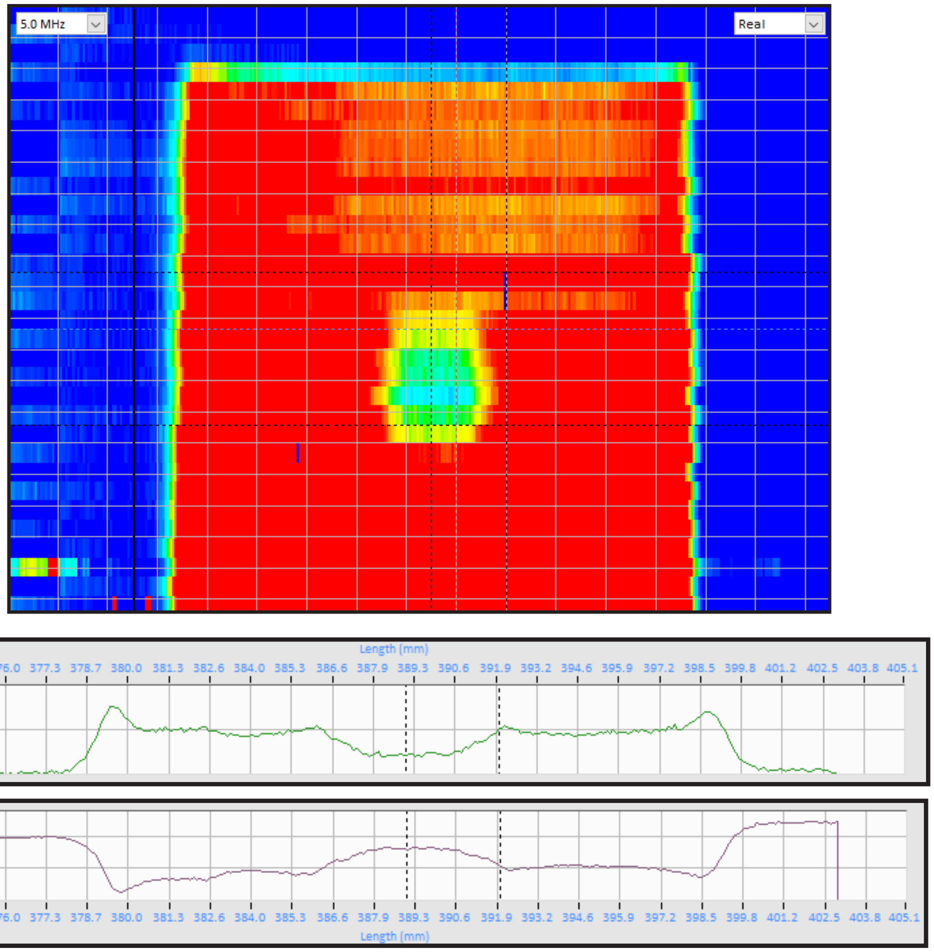

Figure 5: Eddy current scan of a cube design with a pocket of lack of fusion engineered into the center.[4]

Integration of Sensors into AM Systems

Data acquisition and correlation to varying quality conditions is only half the story when evaluating potential in-process monitoring techniques. The other half revolves around ease of integration. Metal AM processes are time-intensive; any extra time added for inspecting a layer gets multiplied across the production of the part. Therefore, acquisition characteristics including field of view, acquisition speed, and processing time become critical for adoption into commercial systems. For example, three-dimensional structed light macroscopes may provide the best means for acquiring surface topography data, but its field-of-view is dictated by its lensing (designed to reach resolution under 10 mm). Rastering and stitching the sensor across the entire powder bed is a potential solution but could add significant time to a given layer period. Array eddy current may provide key data on near surface flaw detection, but sweeping through the number of coils necessary to scan a full bed area may increase the layer period to an unacceptable duration. Thermal melt pool imaging may be an integral source of quality data on process stability, but processing thousands of images acquired per layer may add substantial time to layer period. Unfortunately, many of the off-the-shelf sensing techniques are not optimized for L-PBF. They may maintain the necessary resolution for quality detection, but fail on the field-of-view.

Understanding the applicability of sensor integration into the manufacturing operation for commercial additive machines is critical. Furthermore, optimization of sensing techniques for the L-PBF, and more generally, metal AM environment will be crucial for better quality control methodologies.

Conclusion

A key component to mainstream adoption of metal AM processes is developing robust quality control methodologies to take advantage of the layer-by-layer manufacturing characteristic of AM processes. Many commercial options for sensing exist for both local (melt pool) and global (build area) interrogation of the part, but the current challenge is understanding which techniques offer the best performance in terms of quality measurement and seamless integration into the manufacturing operation. EWI is using open architecture systems, an extensive library of sensors, and its welding engineering, controls and integration expertise to meet the challenge.

References

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