In-process Monitoring and Detection of Cross-contamination in Laser Powder Bed Fusion Additive Manufacturing

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Additive Manufacturing

For centuries, parts have been manufactured via one method: subtraction. In this process, material is melted, formed into a billet, and then machined per the specified part dimensions and features. In the late 20th century, researchers across the world developed a technique for three-dimensional prototyping that flipped the conventional wisdom of part manufacturing on its head. The idea represented the inverse of conventional manufacturing techniques because it was additive in nature, instead of subtractive. This technique involved the deposition of material hatch-by-hatch as opposed to the removal of material chip-by-chip.

Since then, several techniques and processes have been developed, following the same concept of additive manufacturing (AM) or three-dimensional printing (3DP). The market for consumer-grade printing systems or so-called "desktop printers," which can be used to build polymer parts, has flourished and posted double-digit growth metrics in 18 of the last 27 years. In fact, this subset of the AM industry has grown from $100M in 1993 to over $4B in 2014.[1] Progress has been slower on the metals side, specifically with powder bed fusion (PBF) processes. One reason for this slow adoption is the lack of robust quality-assurance programs for PBF parts.

In-Process Monitoring

The term "quality assurance" carries a different connotation when considering parts printed for prototyping versus parts produced for real-world use. Current quality-control methodology is open-loop based on the assumption that repeatable quality will result as long as the process inputs remain constant. When using powder-based AM components in critical applications on planes, spaceships, rockets, and vessels, this assumption does not suffice.

In-process monitoring is a necessity for any powder-based AM quality assurance program. The data collected can be used to reduce overall build times by aborting builds when irreparable defects are present, triggering remedial actions to "save" parts, and helping to guide post-process nondestructive evaluation (NDE) by recommending points of inspection interest. The challenge is to identify what variables determine part quality, what process signals are correlated to those variables, and how these signals can be monitored. Contaminants introduced during the additive manufacturing process, regardless of their origin or composition, are bound to have potentially deleterious effects on quality, as their inclusion within the build will induce process instability and lead to the formation of volumetric defects as well as metallurgical mismatch within the part.

Case Study: In-process Monitoring of Cross-contamination

This case study briefly describes recent achievements in monitoring and detection of cross-contamination during the laser powder bed fusion (L-PBF) process.

This study was part of a larger America Makes program led by EWI. The program looked to provide initial insights on which quality-monitoring signals can most effectively predict L-PBF part quality. This was made possible through the design, fabrication, and operation of EWI's L-PBF sensor test bed for evaluating quality signals in an open architecture environment.

Rectangular specimens measuring 10mm × 10mm × 15.2mm were fabricated with virgin Inconel 625 powder. Virgin tungsten powder was selected as the contaminant material to be deposited in-between processed layers. A carbon-steel plate was used as the build platform.

Contamination levels were categorized into two groups, with three levels per group. The “static” group contained L1, L2, and L3 levels where the contaminant powder was deposited while the recoater was stationary. The “dynamic” group contained L4, L5, and L6 levels, where the contaminant powder was deposited while the recoater was in motion.

Data Acquisition

Two data acquisition sensors were used in this program: a photodetector and an optical camera. This article focuses on data collected by the photodetector. Figure 1 illustrates the characteristics of signals generated by the photodetector. Each data set is representative of one hatch line. A hatch line represents the displacement of the laser spot along a straight line connecting two locations. Any two neighboring hatches have a pre-defined overlap and multiple hatches are used to cover a given surface area. In data set “a,” no peaks are observed. In data set “b,” a single peak is visible. In data set “c,” multiple peaks can be seen. These characteristics can be used to correlate the collected data to the level of contamination, as well as to the contamination profile. Image “d” illustrates the distribution of tungsten powder on the powder bed, where Lc and Wc refer to the length and width of the contaminant powder profile, respectively. The black dashed arrow shows the recoating direction.

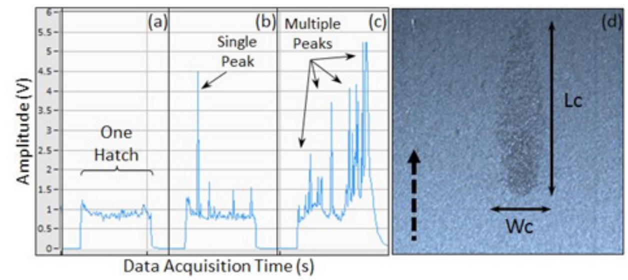

Figure 1: The characteristics of signals generated by the photodetector

Figure 2 illustrates the six contamination profiles with their associated photodetector data. The black arrow shows the laser scanning direction as well as the recoating direction. Data were collected from six consecutive hatches and were equivalent to 0.1 seconds of laser scanning. The number of peaks per hatch, the intensity of those peaks, and the number of hatches with high-intensity peaks are the three primary data provided by a photodetector. It can be concluded from these results that L3 and L6 have the high contamination levels due to the formation of high-intensity peaks. Also, the increased number of L5 hatches with high-intensity peaks, compared to L2, correlates with the longer profile of the tungsten powder.

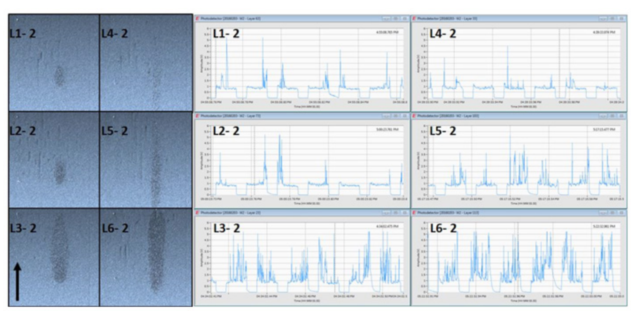

Figure 2: Correlation between the contamination profile and the photodetector data

Metallurgical Analysis

Post-process analysis can provide additional information to support and explain the findings of in-process monitoring. Figure 3 illustrates an energy-dispersive X-ray spectroscopy (EDS) map prepared from a tungsten-contaminated layer. The minimal dilution around the tungsten particles is attributed to the high melting temperature of tungsten and the application of laser parameters that were optimized for Inconel 625.

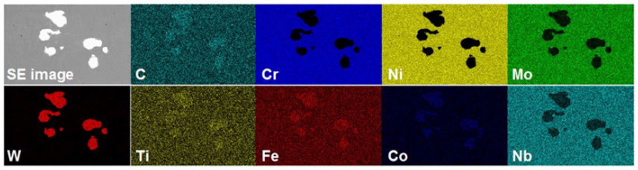

Figure 3: EDS map of a tungsten-contaminated layer in an Inconel 625 matrix

X-Ray Computed Tomography (CT)

Metallurgical analysis is a fast, low-cost technique for gathering information about the contaminated layer; however, it is limited to a single cross section. X-ray computed tomography (CT) is another post-inspection technique that can provide additional information on the three dimensional distribution of contaminants.

The x-y distribution of the tungsten powder was studied for three layers before and eight layers after it was deposited (Figure 4). The white arrow indicates the recoating direction. Even though the contaminant powder was deposited in layer n, some indications of contamination were observed in the layers below (n-3 through n-1). The presence of contamination in these layers is attributed to the penetration and fluid flow of the molten pool, which transferred the tungsten powder to the underlying material. An almost identical behavior was observed above the contamination layer, where the contamination was spread up to layer n+7 after its introduction.

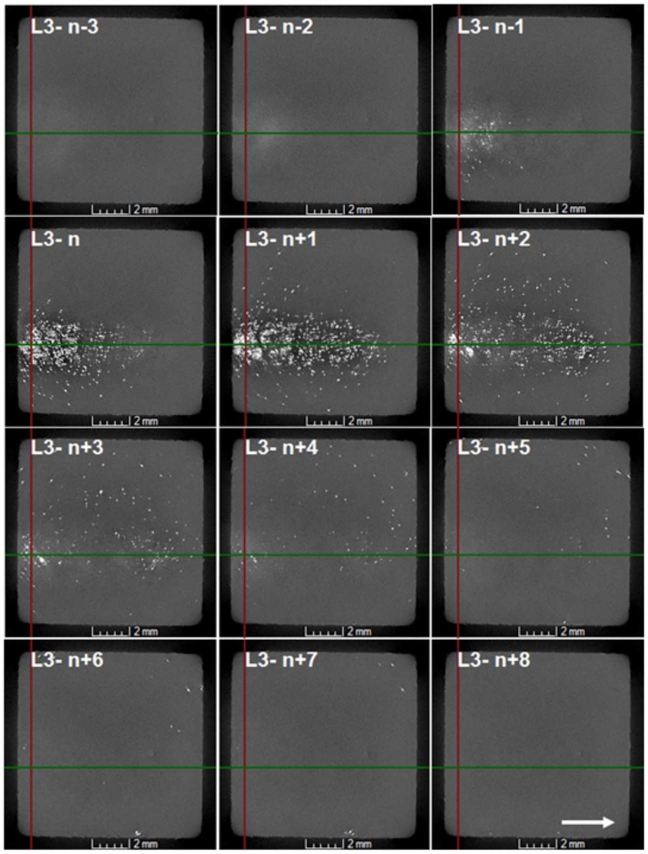

Figure 4: Spread of tungsten powder contamination in specimen L3 after deposition at layer *n*

Conclusion

Although some studies have been conducted on in-process monitoring of PBF processes, further development of such techniques is required. Optimization of current monitoring methods, combination of multiple techniques where each can fulfill one requirement, and the creation of new monitoring methods are among the viable solutions. Regardless of the progress of the AM industry, the development of in-process monitoring techniques is an absolute requirement for the full and broad utilization of PBF processes.

EWI's PBF Capabilities

EWI's open-architecture L-PBF test bed is equipped with several in-process monitoring sensors in addition to the photodetector described in this paper, and is capable of laser path planning. EWI has a significant number of additional capabilities to support cutting-edge development of PBF processes. These include an EOS M280 L-PBF system, an Arcam EBM electron beam powder bed fusion system, an induction plasma powder spherodization system, and a particle size analyzer. EWI also maintains non-contact quality measurement capabilities including an Alicona profilometer for automated high-speed production applications, a computed tomography system for through-thickness inspection of complex components, and a provisionally patented powder handling system for the fabrication of multi-material metallic components.

1. Wohlers, T. and Caffrey, T., *Wohlers Report 2015*, p.120, (2015)

Mahdi Jamshidinia *is an Application Engineer in EWI's additive manufacturing (AM) group where he is responsible for the operation of EWI's EOS M280 and Standard Test Bed (STB), both laser powder bed fusion (L-PBF) machines. He is the primary investigator on multiple AM projects, and conducts experiments to develop process parameters for new materials on the L-PBF equipment. Mahdi's technical specialties include additive manufacturing, materials characterization, mechanical testing, nondestructive inspection, and numerical modeling.*

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