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Insights into Powder Flow Characterization Methods for Directed Energy Distribution Additive Manufacturing Systems

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Abstract

Powder-blown Directed Energy Distribution Additive Manufacturing systems often feed powdered metal into a melt pool generated by a laser. As the laser is moved, the melt pool solidifies, leaving behind a deposit. Such depositions may be built up into full components or used to add features on existing components. Distribution and uniformity of the powder flow is critical to achieve uniform and predictable depositions. For example, small deviations at the minute-level (cf. the resolution limit of the deposition) can propagate to gross deviations at the component-level. Meanwhile, large deviations in the powder flow can be yet unobservable to the naked eye, but produce catastrophic effects within small depositions. Such depositions are common to repair applications targeted at ARL Penn State, wherein relatively small deposits are created on larger, critical components. Novel and re-purposed OEM tools are compared to study these powder flow behaviors, providing new insights into process variability.

Introduction

There are two primary Additive Manufacturing (AM) technologies used for metals-based work: Powder Bed Fusion (PBF) and Directed Energy Distribution (DED) systems. Both technologies are readily used for full component fabrication. However, DED systems have clear advantages for the repair and sustainment of existing high-value components.

The Applied Research Lab (ARL) has been active in developing and qualifying laser-based DED repair for different commercial and military applications. The inherently low-heat-input process afforded by laser-based DEDAM has been exploited to minimize resultant component distortion, while yet producing high-quality, fully-fused depositions. Laser-based DED is typically conducted with wire or powdered feedstock. Most process parameters must be carefully controlled to minimize variability during critical processes. As such, application-specific advantages of employing the powder-blown process have been tempered by the effective inability to measure and/or characterize the powder flow, beyond simple measurements of overall flowrate. It has been shown that an irregular powder flow can introduce defects in the as-built part [1]. Prior studies have attempted to observe the effect this powder distribution has on final cladding results by raising and lowering the working distance, changing the position of the melt pool relative to the focus of the powder distribution [2]. Other studies have modeled the flow of powders by predicting particle trajectories due to gas flow and laser processing conditions [3]. Very little success, however, had been gained to measure and characterize the actual powder flow of a given DEDAM process.

Preceding ARL studies led to the development and prototyping of novel powder flow characterization methods/tools as well as examining and evaluating other commercial-off-the-shelf tools used for other applications that could be repurposed to measure/evaluate powder flow for DEDAM systems, the primary goal being to reduce variability in depositions. Methods/tools used to characterize DEDAM powder flow included:

- 2D Carbon Paper Impression
- 3D Custom Laser Profiler (misnomer...actually a 2D measurement as well)
- 2D Laser Line Scanning
- 1D Knife-Edge Profiler
- 2D OEM Laser Profiler

The “2D Carbon Paper Impression” method was considered first, whereby a piece of carbon paper was mounted beneath the DED system powder flow nozzles for a fixed time (cf. 60 s), and then analyzed to assess characteristics of distribution and intensity for a given distance from the nozzles. Corresponding images in Figure 2, for example, show a distinct difference in the impressions before and after switching from an old set of nozzles to newer ones.

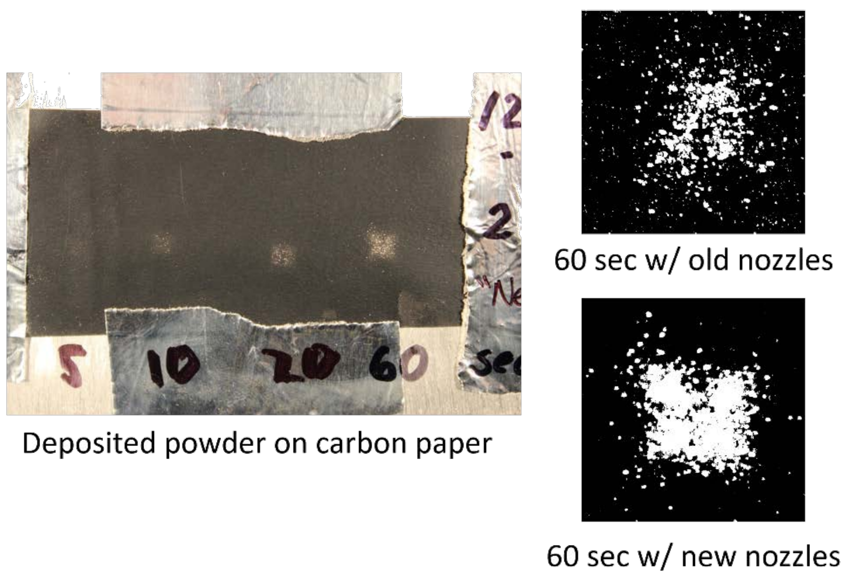

Figure 1: 2D Carbon paper impressions/datasets

The “3D Custom Laser Profiler” method was then developed (Figure 3), which utilized a diode laser to illuminate a plane in space, then imaged by an orthogonally-located camera, and scanned (via external stages) through the field of powder flow. Stacks of images were combined in software (e.g., Avizo) to reconstruct full 3D profiles of the (time-averaged—hence the “misnomer” comment above) flow field. An integrated prototype tool based on this method was partially designed, but dismissed, in lieu of alternate prospects.

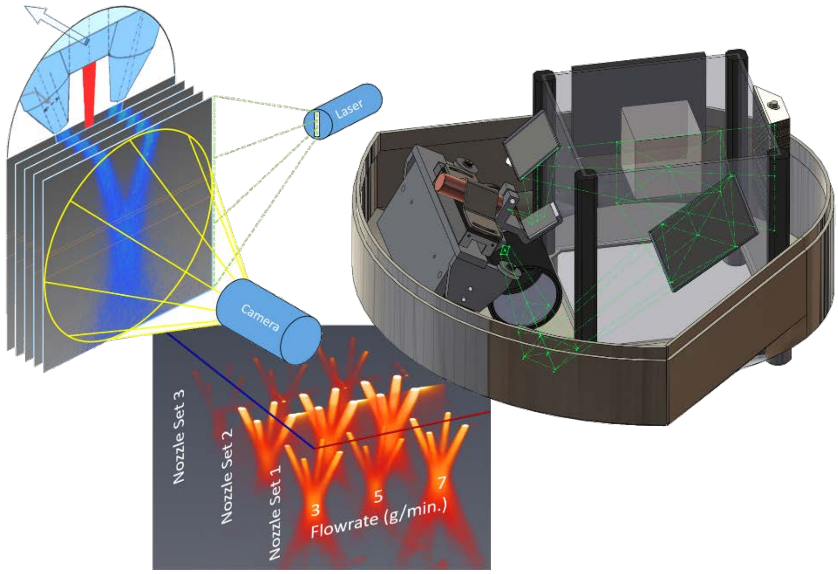

Figure 2: 3D Custom Laser Profiler method and representative datasets

The “2D Laser Line Scanning” method was considered, utilizing an integrated coaxial camera within a specific DED system at ARL’s Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D). Similar to the method above, this used a diode laser to illuminate the horizontal plane that was imaged by the (orthogonal) existing DED system camera/optics. An extended exposure of this plane offered a perspective of the horizontal powder trajectories (Figure 4) not visible from single-vertical-plane (time-averaged) images using the “3D” method previously described.

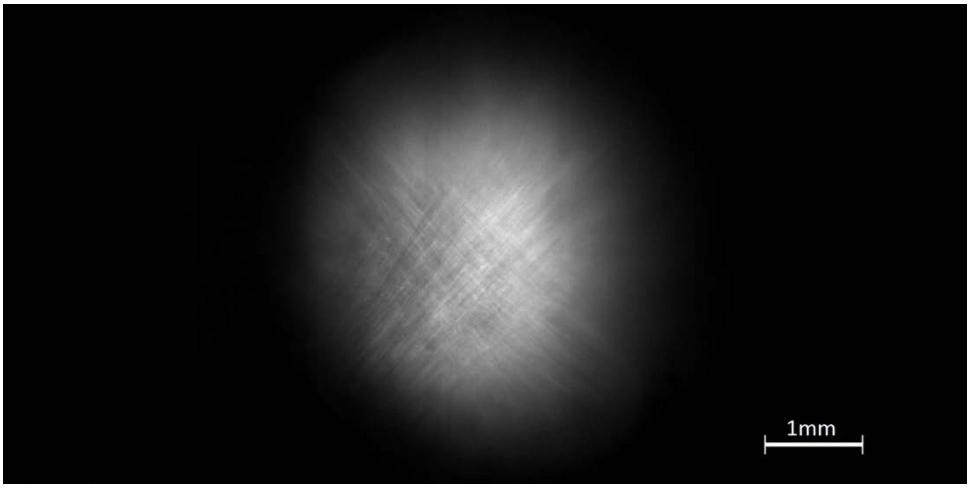

Figure 3: 2D Laser Line Scanning image of coalesced powder from four nozzles

A “1D Knife-Edge” method was developed, based on analogous measurements used to estimate laser beam widths (by blocking a portion of the beam while measuring the resulting power). A knife was here used to split the powder flow into two streams that could be weighed in real-time. Although either scale would ideally offer a complementary perspective of the flow, we found the capture efficiency was not 100% and that using two scales provided additional insight. A prototype tool was built, as depicted in Figure 5. It was considered the first (of two) "primary" tool of interest moving forward.

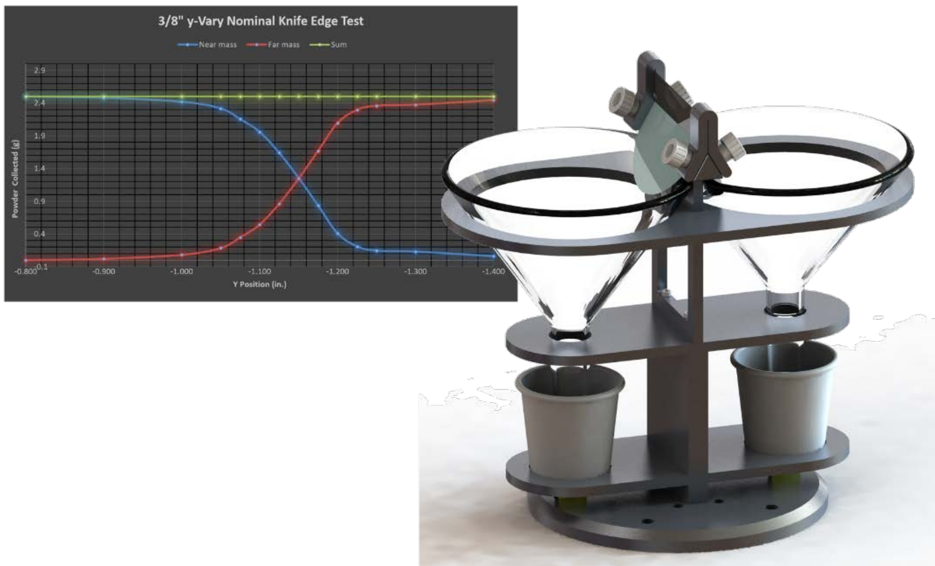

Figure 4: 1D Knife-Edge Profiler with representative dataset

Finally, a "2D OEM Laser Profiler" method was found that could image the powder flow via the analysis of an OEM tool's raw data to achieve comparable results to the "3D Custom Laser Profiler" method consider previously. A simple fixture was built to manipulate this tool during follow-on studies. This tool was considered as the second (of two) "primary" tool of interest.

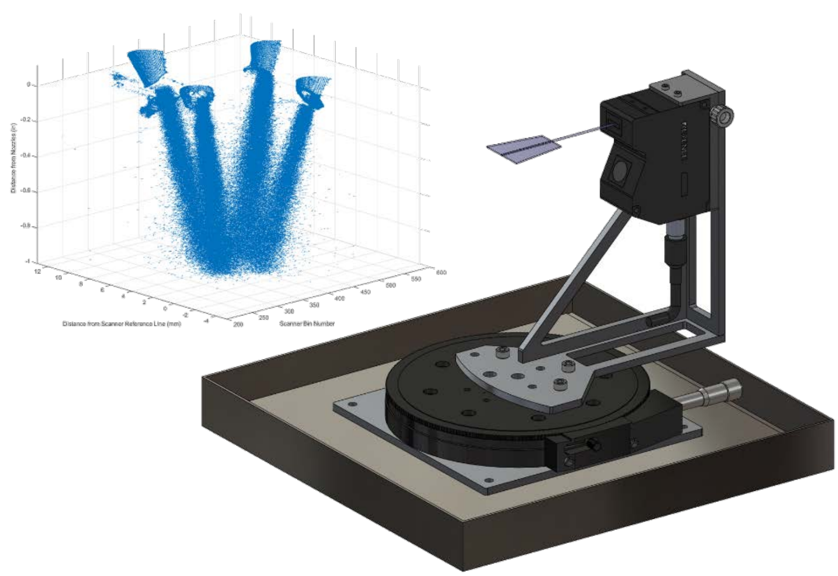

Figure 5: 2D OEM Laser Profiler with representative dataset

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A study was thus initiated to:

- Compare and contrast the two primary characterization methods/tools
- Use the primary tools to characterize powder flow in a specific DEDAM system, and
- Test correlation between measured flow characteristics and subsequent depositions

Approach

Equipment utilized included:

- DED System: Optomec LENS MR7
- Powder measurement tools
    - 1D Knife-edge Profiler
    - 2D OEM Laser Profiler (Keyence LJ-V7080)
- Materials: Inconel 625 powder
- Deposition measurement: FARO Edge 14000

The DED Optomec LENS MR7 (Figure 7) employs a 500W IPG fiber laser to melt powdered feedstock that is directed (via assist gas) toward a melt pool via 4 nozzles in an atmosphere-controlled chamber. As the substrate is moved, the melt solidifies and generates the deposition. The copper nozzles are easily replaced upon contamination, damage, etc.

Powder is being blown through the nozzles in the image below (Figure 7), though it is difficult to observe. Similarly, changes to the quality of the nozzles and the localized effects on the deposition can also be difficult to see. Once a build is completed using deficient nozzles that compromise the flow characteristics, or has failed mid-way because of a gross problem, it is passed the point to apply corrective solutions.

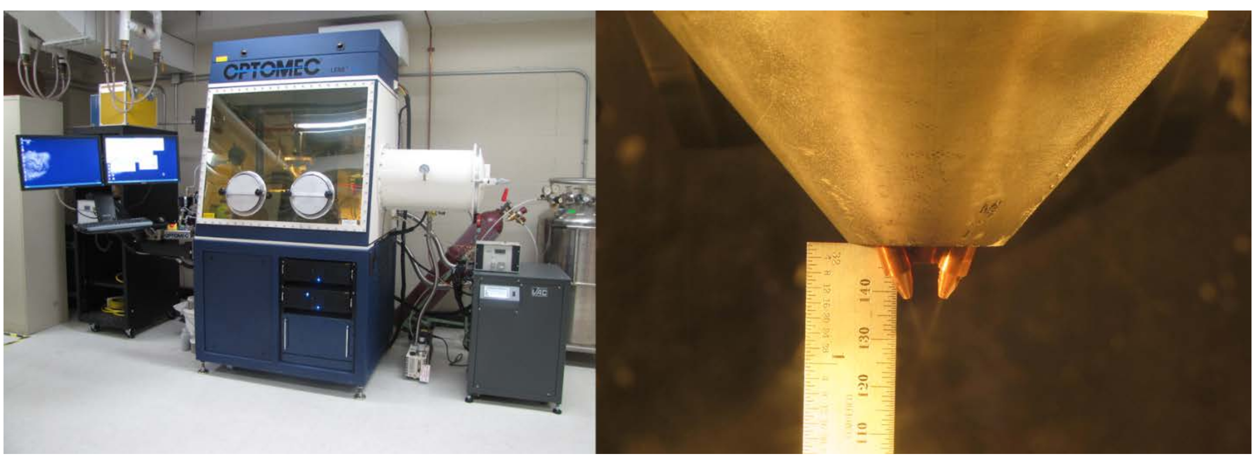

Figure 6: Optomec LENS MR7 DED system (left) and powder nozzles (right)

The 1D Knife-edge Profiler (Figure 8) employed two Futek LSB200 10 g load cells, with resolutions as low as 0.0003 g. Powder is collected into paper cups via flat-sided glass funnels after being sectioned with a straight razor blade.

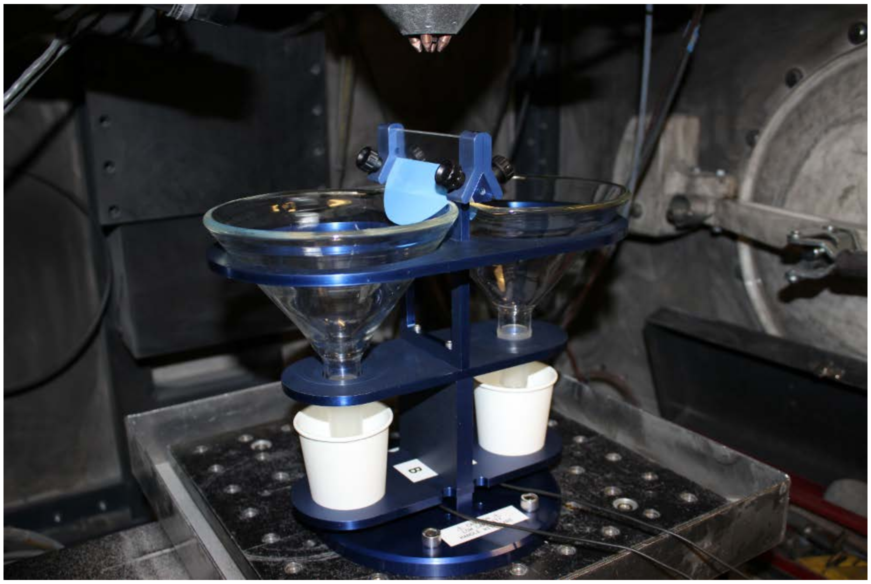

Figure 7: 1D Knife-edge Profiler

The 2D OEM Laser Profiler re-purposed a Keyence LJ-V7080 2D surface profilometer, with a spatial resolution of 50 µm, over >30 x 30mm field, at a sampling rate of 2 kHz. The high-speed sampling rate was useful to avoid shadowing effects.

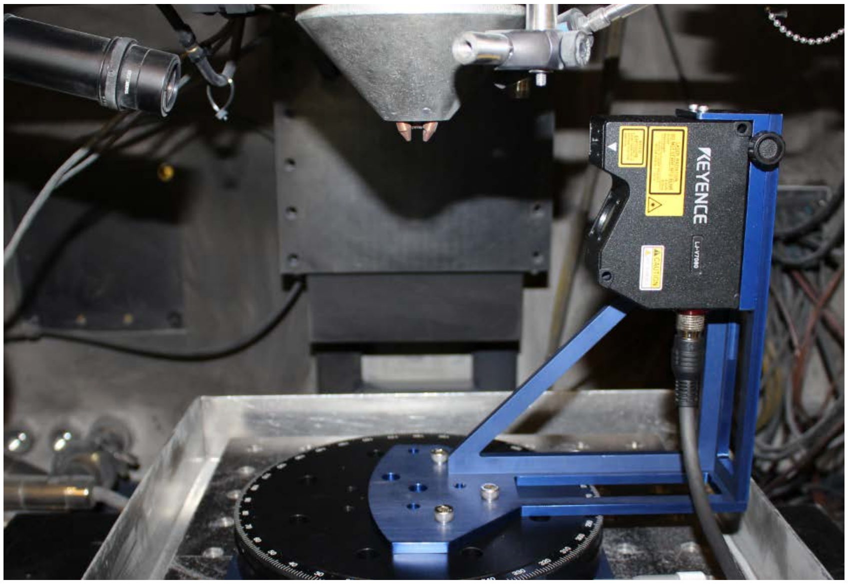

Figure 8: 2D OEM Laser Profiler

Gas atomized Inconel 625 powder from Carpenter, with a mesh size of -80/+325, was used for the case study.

Results

A comparison (Figure 10) between the primary powder measurement tools showed a clear favorite of the 2D OEM Laser Profiler for industrial use, with one caveat: the indirect nature of the measurement requires calibration via another tool, like the 1D Knife-edge Profiler.

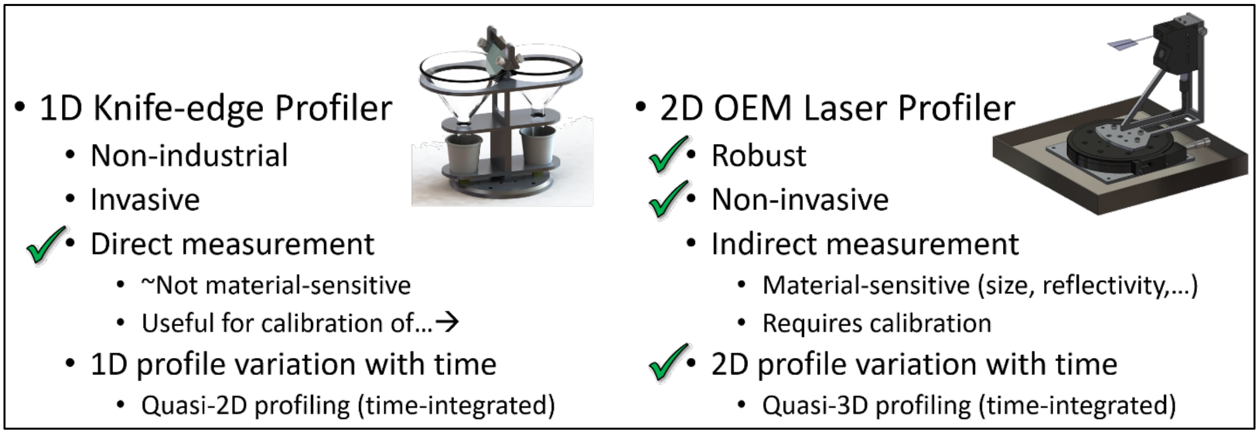

Figure 9: Powder measurement tool comparison

Raw output from one scale on the 1D Knife-edge Profiler is shown in Figure 11 (top), as a plot of flowrate vs. time. Under ideal circumstances, this graph would transition smoothly from a zero-flowrate (when all of the powder was directed on the opposite side of the blade from the scale) to a constant flowrate (when all of the powder is collected by the scale, as depicted in Figure 12 (top)). Knowing velocity with which the tool was passed beneath the powder, the time scale could be transformed to distance, and the full Cumulative Distribution Function (CDF), could be differentiated to find the (normal) flow distribution, and calculate properties such as flow diameter (based, e.g., off principles similar to laser beam characterization techniques.) A previously unknown oscillation in the real flowrate was, however, observed.

A curve-fitting model was generated based off of a Fast Fourier Transform (FFT) analysis of the real oscillation and a CDF. These were then used to define the magnitude and frequency of the unwanted oscillation/noise, in addition to the average waist diameter at the measurement plane.

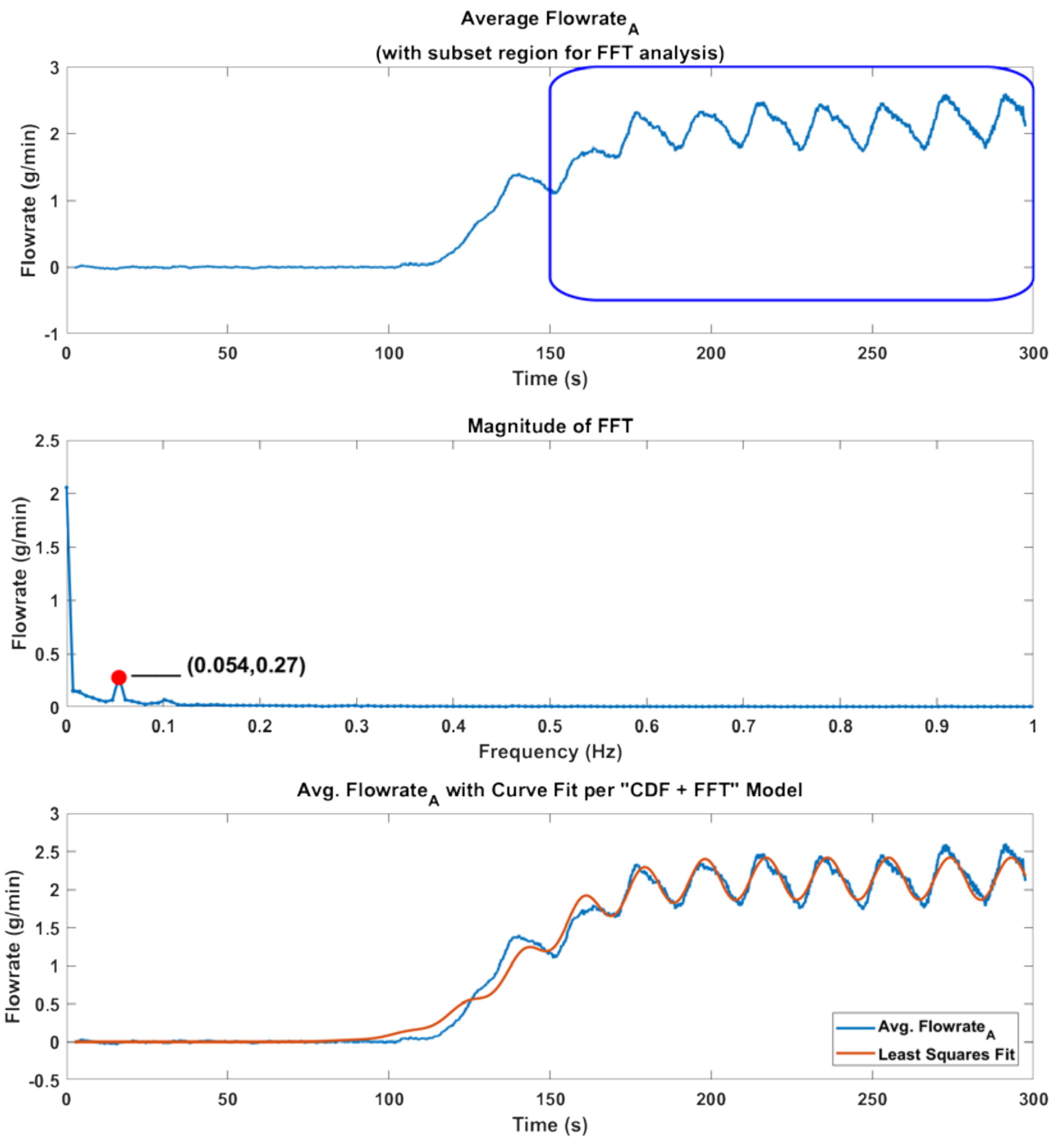

Figure 10: 1D Knife-edge Profiler data with CDF + FFT curve fit

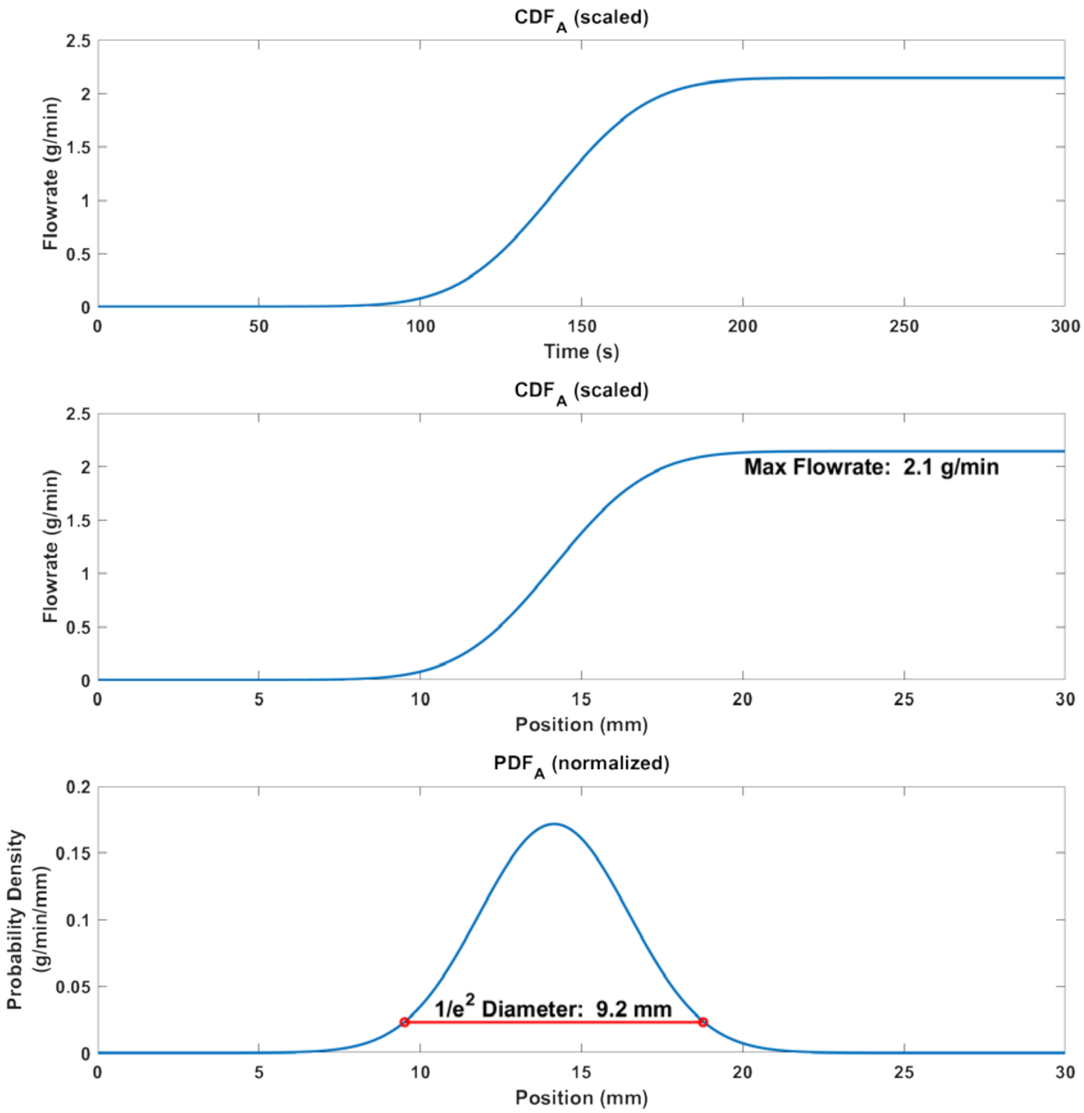

Figure 11: Idealized (i.e., no oscillation), curve-fitted portion of 1D Knife-edge Profiler data

The 1D knife-edge method takes a direct measurement of the powder flow, but the (prototype) tool is not industrially robust. The measurement is invasive by its very nature, and can introduce error during use. Data is integrated spatially along the knife, and may be used to produce a quasi-2D (i.e., time-dependent) mapping of the flow field.

Raw data collected from the 2D OEM Laser Profiler contain sparse indications of powder reflections. Individual samples (500 μs) are superposed with adjacent samples (perhaps 250 ms total) to generate a sufficient 2D spatial flow profile, which may be analyzed to determine flow diameter (and more). A superposition of many more frames provides a time-averaged flow profile, as shown in Figure 13.

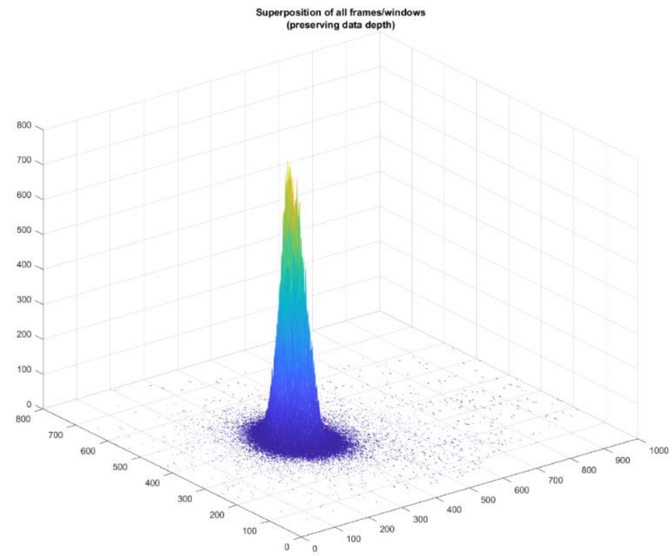

Figure 12: Superposed data frames from 2D OEM Laser Profiler showing average flow profile over 80 s duration

The 2D OEM Laser Profiler was used to collect time-varying data for fixed spatial planes, as shown in Figure 14 and Figure 15. Flowrate magnitudes for these indirect measurements were deduced by directly scaling the number of reflections observed in the measurement against the real flowrates measured with 1D Knife-edge Profiler. FFT analyses of these data show identical trends observed with the 1D Knife-edge Profiler, but can here also differentiate between individual nozzles (Figure 15).

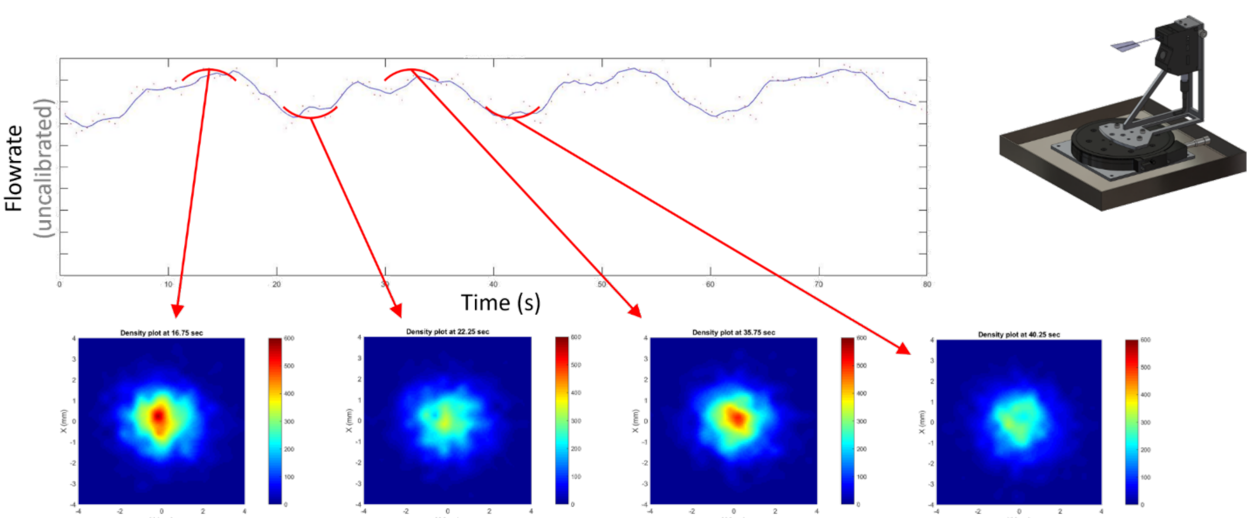

Figure 13: 2D OEM Laser Profiler data collected at convergence point of powder streams

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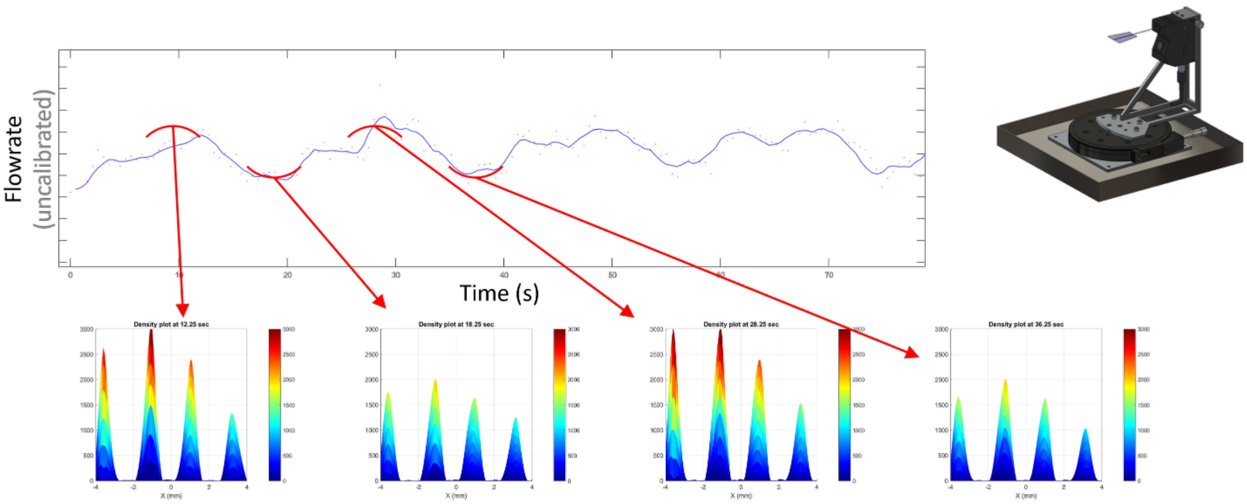

Figure 14: 2D OEM Laser Profiler data collected at exit of powder nozzles

The 2D profiler results are collected indirectly, via a non-invasive, industrially-robust package. It can generate 2D and quasi-3D (i.e., time-dependent) mappings of the flow field.

The Optomec LENS machine at ARL Penn State has two power feeders, one of which has been more heavily used than the other. Oscillatory flow frequencies observed with both profiling tools were found to be linearly dependent on the feedrate, but the magnitudes of this noise were only a function of the powder feeder used. The feeder having more operational hours introduced more noise, with harmonic amplitudes on the order of 20% of the total desired feedrate, and periods on the order of 15 – 20 seconds at common feedrates.

Long, serpentine bead-on-plate depositions were made to assess possible time-varying characteristics and directionally-sensitive geometries. A FaroArm scanner was used to measure the bead heights, with four or three nozzles (one nozzle plugged). Bead geometries were qualitatively contrasted, as shown in Figure 16, to assess the effect of a plugged nozzle. Such geometries were programmatically analyzed along the bead length to tabulate the cross-sectional bead area as a function of time, as plotted in Figure 17.

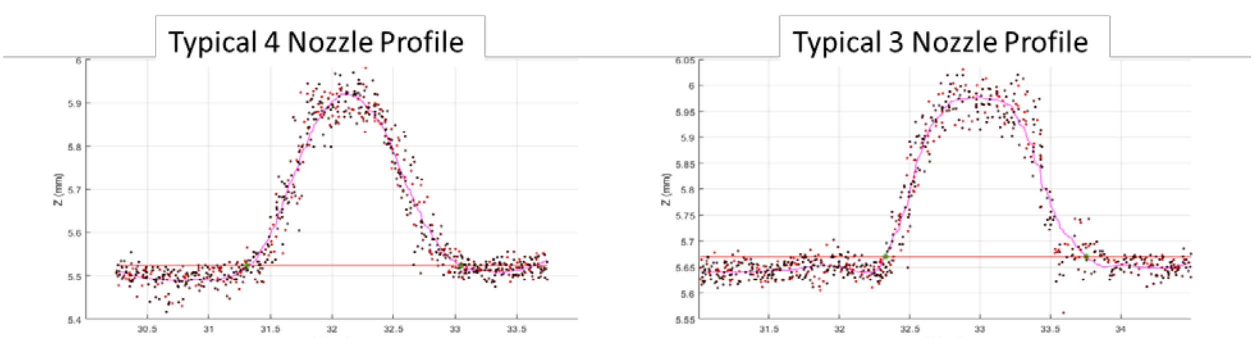

Figure 15: Typical deposition profiles using 4 (standard) or 3 (one quadrant plugged) nozzles

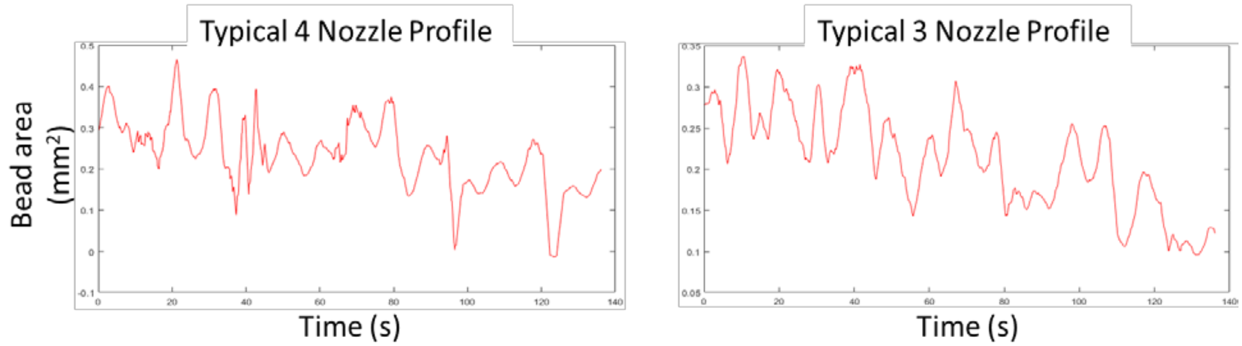

Figure 16: Variation in deposition bead area over time

FFTs of the deposition cross-sectional areas were consistent with that of the overall powder flowrates—showing harmonic variation within 10% of the predicted values from the flowrate measurements alone.

Conclusions

Characterization and control of feedstock is a paramount concern in DEDAM. Powder-blown DEDAM introduces characterization challenges that have been met through novel techniques, utilizing commercially available equipment. Using these tools, variability in depositions has been directly mapped to (previously unknown) variability in the powder flow, which is equipment-dependent and controllable.

A calibrated 2D OEM Laser Profiler has been shown to be industrially robust and able to provide valuable insight into the powder flow, including spatial and temporal fluctuations in the flow field. Such powder flow characterizations are strongly recommended as a standard procedural step during process setup for all critical depositions. Defining and bounding acceptable ranges of the flow characteristics must be a part of process specification and/or qualification documentation.

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The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of The Naval Sea Systems Command or the U.S. Government.

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