Laser Power Accuracy of Additive Manufacturing Systems – A Round Robin Study

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High power lasers are at the core of metal additive manufacturing (AM) systems and the accurate delivery of laser energy is critical to part performance. We have performed a round robin style survey of U.S. AM equipment across industry, academia, and government facilities. Using a low uncertainty (1.3 %, *k*=2) thermal power meter, we assessed the accuracy to which these systems delivered laser power and how accurately the process engineer was able to measure this with their power meter. We have found that although on average instruments accurately deliver laser power, there is a large spread in values (5.6% – 14.1%), which poses a heretofore unknown challenge for process development.

INTRODUCTION

Laser powder bed fusion additive manufacturing (LPBF-AM) is a revolutionary manufacturing technique whereby complex, near net-shaped metal parts are made in a single processing step. At the core of this technique is a focused high-power laser that is rapidly scanned over a metal powder bed surface, building the part in a layer-wise fashion. The deposited laser energy largely determines the metal thermal history from melt through solidification and microstructure development, which directly affects part performance. Therefore, it is critical that the laser power delivery is accurate and known. In fact, the ISO/ASTM standard for AM equipment operations (ISO/ASTM TS 52930:2021(E)) lists laser power first among its critical process input and output variables [1].

Typical LPBF-AM systems use a near infrared, continuous-wave laser operating between 50 W and 1000 W. Typically, during initial commissioning and at regular service intervals, laser power output is calibrated by a technician who uses a commercial-off-the-shelf (COTS) power meter with a typical uncertainty in the range of 3-5%. Although most operators generally consider these laser systems to deliver stable output power, several events can occur which degrade performance. These include drift due to thermal effects, optics degradation, or near end-of-life laser operation.

Absolute laser power measurement is critical for LPBF-AM for several reasons. First, industrial process development is a time-consuming and costly endeavour. Once a suitable process is found, mass production requires that it be deployed across several machines that may be different makes and models and in different facilities. Ensuring the accurate transfer of the process parameters requires absolute metrology. Second, industry strives to use predictive simulations of the LPBF-AM process to reduce process development time. Again, implementing simulation optimized processes requires that the factory-floor system accurately delivers the simulated laser power.

METHODS

Our study measured laser power delivery LPBF-AM systems under nominal ‘real-world’ operating conditions. Each machine was measured with a standard procedure whereby the operator was first asked to measure laser power output at predetermined powers with their power meter. Next, we measured

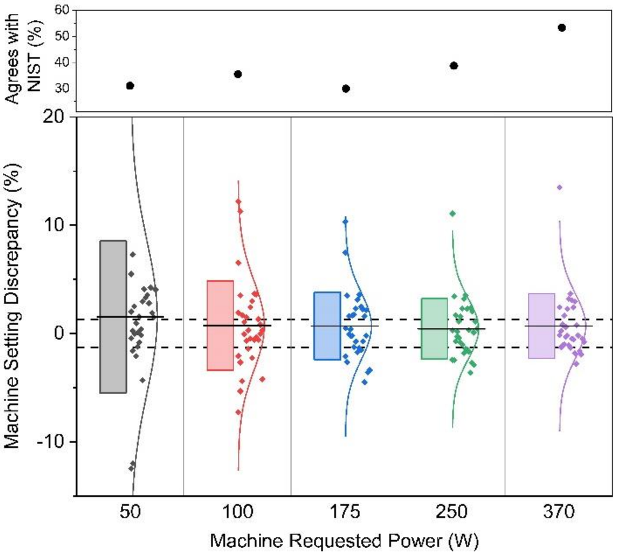

Figure 1. The discrepancy in actual delivered power versus that requested from the LPBF-AM machine as a percent difference from the NIST measured value.

the same laser powers with our low uncertainty (1.3%, *k*=2) transfer standard power meter. We are therefore able to compare three values: the laser power requested from the machine, the value measured by the operator, and the value measured by the NIST device. We treated the machine requested power as a non-experimental number with zero uncertainty, and we used manufacturer-stated uncertainties of the participant's power meter.

We wanted to assess LPBF-AM systems in general so did not limit our study to a particular system manufacturer. Presently, we have measured 7 different models from 4 manufacturers. Our study includes 12 participant facilities, whose identity is intentionally withheld. In total, we have measured 31 lasers from 25 LPBF-AM systems.

RESULTS AND DISCUSSION

The aim of our study was to address and quantify two basic questions: 1) How likely is a particular LPBF-AM system to deliver the commanded laser power? and 2) How well is an operator able to determine the accuracy of their system's laser? Figure 1 addresses the first. Here, we show measurement results as the difference between the NIST-measured value and the machine requested value, normalized by the NIST value. Therefore, a value of zero would mean that the laser is in perfect agreement with the NIST measurement. The horizontal dashed lines above and below zero represent the NIST power meter uncertainty. The boxes to the left of the scatter plots show the mean values (dark, horizontal lines) and extend above and below by one standard deviation. The solid curves model the data points as a Gaussian distribution.

These results show that from 100 W to 370 W, the average laser power output agrees with the NIST-measured result. At 50 W, the average is just slightly above our uncertainty. The plot above the scatter plot shows the percentage of lasers that fall within the uncertainty of our detector. These range from 31% to 53%. Although it may appear comforting that the average values generally agree with our measured value, the challenge for AM process development is that one does not make a part on an *average* machine, but rather on a *specific* machine. Therefore, it is more instructive to look at the spread of possible values across all machines that we define as twice the standard deviation at each power level (i.e. the full extent of the shaded boxes), which range from 5.6% to 14.1%. This poses a potential problem for developing processes for difficult-to-manufacture alloys found in medical and aerospace applications where process parameter windows are believed to be about 1%.

Our study also found that having multiple machines of the same make and model co-located in the same facility did not eliminate this spread. One facility had 9 such systems located within a few meters of one another. The spread in values was lower at 2.9% to 4.6% but still higher than process engineers would like.

Figure 2 addresses how well an operator can accurately measure laser output power. Participant power meters had manufacturer-stated uncertainties between 3.0% and 5.4% (*k*=2). With the exception of 50 W, the average of these values is very near the NIST measured value, although the spread is larger than typical device uncertainty.

Ultimately, the accuracy to which laser power delivery must be determined is dictated by the manufacturing tolerance of a particular material and application, which is currently an active area of research. Our results show, however, that laser power delivery across machines should not be assumed to be equal to better than 5.6% to 14.1%. Improving this requires a low uncertainty calibration for their power meter, which is possible at a national metrology institute like NIST, but not currently available with commercial-off-the-shelf sensors.

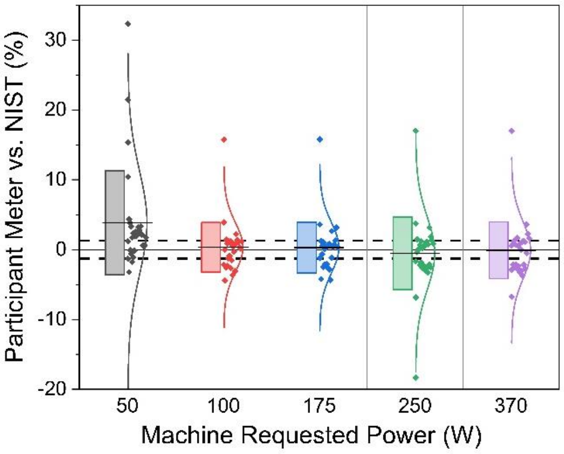

Figure 2. The discrepancy in participant power measurements as a percent deviation from NIST measured values.

REFERENCES

1. Additive manufacturing – Qualification principles – Installation, operation and performance (IQ/OQ/PQ) of PFB-LB equipment. ISO/ASTM TS 52930:2021(E), Geneva, Switzerland, ISO/ASTM International. https://www.iso.org/standard/7927.html