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Are Additive Manufacturing systems accurately delivering laser power?

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Abstract

At the core of most metal additive manufacturing (AM) systems is a high-power (100-1000 W) laser. The delivered light energy drives the entire AM process by determining the melt volume and maximum temperature, which ultimately dictates solidification and microstructure behaviors. Therefore, accurate laser power measurement and delivery is critical to part quality. To this end, the National Institute of Standards and Technology is undertaking an anonymized, "round-robin" assessment of laser power delivery in U.S. AM systems in "real-world" manufacturing conditions. We use a low-uncertainty power meter (1.3%) to compare actual laser power with both the requested output and the operator's own measurements. We have found that the calibration frequency of the power meter and laser, as well as operator proficiency, greatly influences accuracy. Ultimately though, the limited uncertainty of commercial meters, up to 5%, presents a challenge for developing narrow process windows necessary for difficult-to-manufacture alloys found in medical and aerospace applications.

Keywords: Additive Manufacturing; Laser Power; Metrology

1. Introduction

The entire laser powder bed fusion (LPBF) additive manufacturing (AM) process relies on the delivery of optical energy to a powder bed substrate. In most commercial systems, optical energy is provided by a near infrared, continuous-wave laser. Although there are many important parameters for determining the final build quality of an AM part, the ability of a laser to provide accurate and reliable energy to the powder bed ranks highly among them. 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. Here we describe a study underway to assess the accuracy with which such systems can deliver laser power.

1.1. Laser power measurement and accuracy

Standard commercial instruments for measuring laser power in the range typical of AM systems (100 W – 1000 W) have manufacturer-reported uncertainties of up to 5 %. These uncertainties are ultimately derived through a traceability chain to a primary optical power standard at a national metrology institute (NMI). The uncertainty of these primary standards is much lower, around 1 %. The increase in uncertainty between the NMI and this field device is due to the number of measurement comparison steps between the field device and the primary standard. As a simple example, an operator's device is calibrated against the device manufacturer's internal standard, this internal standard is then compared to a transfer standard that the manufacturer routinely sends to an NMI for comparison to the primary standard. This example has three links in the traceability chain to the primary standard with each link representing an increase in the customer device's uncertainty. The power meter used by the National Institute of Standards and Technology (NIST) in the study described here has a much lower uncertainty, in part, because these links are removed and the NIST device is compared directly with the primary standard.

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During the initial commissioning of an AM system, the laser output power is calibrated by a technician who uses a commercial power meter. Users are encouraged by some AM system manufacturers and various ASTM standards to routinely measure their laser power output. Although these laser systems are generally regarded as providing relatively stable optical power output, conditions can occur which degrade performance. For instance, laser power can drift due to thermal effects of the laser, dirty optics, or from near end-of-life operation. These relative changes can be compensated through a recalibration of the system during routine maintenance or by replacing the affected optical components.

In addition to relative drifts in laser power, absolute laser power accuracy is critical for AM process development. For instance, so-called P-V process maps are commonly used to determine acceptable ranges for laser power (P) and scan speed velocity (V). For industrial AM applications, it is important that these maps apply across different machines in different manufacturing facilities, in order to reduce the amount of engineering needed to increase production capacity. Furthermore, the digitization of the manufacturing process as desired by Industry 4.0 goals calls for increased implementation of computer simulations to drive AM process development. Realizing these goals will require absolute laser power accuracy in order to implement the laser power prescribed by the simulation to that delivered by the AM system. This is also true of academic AM research that often uses laser power as a variable when studying microstructure, part perfomance, and surface finish. Translating these basic science discoveries into industrial practice necessitates accurate laser power metrology.

1.2. NIST's AM laser power round robin

NIST is currently undertaking a "round-robin" assessment of AM systems in the United States to quantify the accuracy to which laser power is being delivered. This study involves industry, academia, and government facilities and a variety of AM system manufacturers. At each AM system and under standardized conditions, we are comparing three laser power results: 1) the participant's measurements with their own power meter, 2) measurements using a NIST power meter with lower uncertainty calibration, and 3) the laser power that is programed to be delivered by the AM system. These results will then be compiled and published anonymously. Since we want to assess the community in general, and do not want to target a specific AM or laser system manufacturer, we will not include the make and model of the tested instruments. In addition to capturing laser power data, all participants are asked to provide specific information about their AM systems. Questions include age of laser, time since last service, frequency of use, frequency of laser power measurement, and so forth which provide further insight into the determinants of laser power accuracy.

This round robin study is ongoing and at present we have performed measurements of 22 lasers, in 17 AM systems at 7 different facilities. Over the course of the study, we will be more than doubling the number of AM systems included, and thus we are not able to present a full statistical analysis until these measurements are complete. Here we present some initial findings from specific measurements and discuss lessons learned so far.

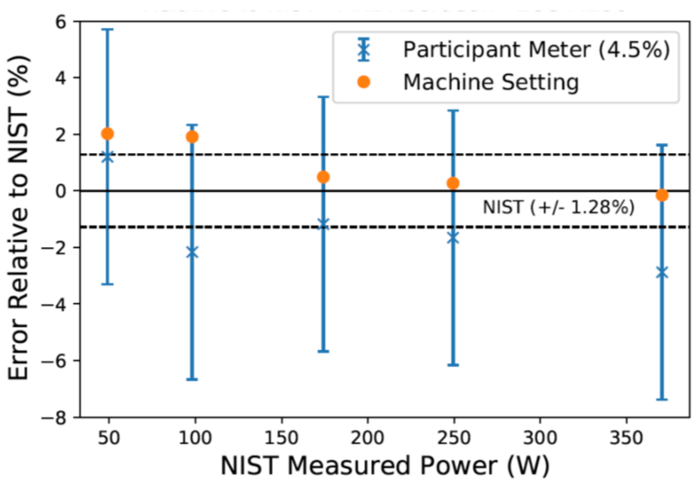

Fig. 1: The power discrepancy of the AM machine setting and that measured by the participant's power meter plotted versus that measured by the higher accuracy (± 1.28 %) NIST laser power meter. The dashed lines represent the expanded uncertainty (k=2) of the NIST power meter. The error bars represent the uncertainty of the participant's laser power meter as reported by the manufacturer.

2. Laser Power Round Robin Results

2.1. A new AM system

In our round robin study, we have encountered AM systems at all stages of their lifecycle. In this first example, we measured the participant's system shortly after it was commissioned by the manufacturer. The participant's power meter was also brand new ("out-of-the-box") prior to these measurements. Fig. 1 shows these results as a relative discrepancy between NIST results and what the participant's power meter measured (blue crosses) as well as the discrepancy of what the AM system thought it was delivering (orange circles). Values closest to zero indicate the best performance. The stated uncertainty of the participant's meter is given in the figure legend in parenthesis and is taken at face-value from the manufacturer's specification. The range of uncertainty of the NIST calibrated power meter is shown as the horizontal dashed lines.

These data show that between 175 W and 370 W, the power measured by the NIST meter closely matched the requested value "machine setting," which indicates that the system is calibrated reasonably well at these powers. However, at 50 W and 100 W, the machine setting is 2 % higher than is being delivered. At every power level, such discrepancies are within the uncertainty of the participant's power meter even though a discrepancy of over 4 % is observed at 100 W. We presume that the technician who initially calibrated the laser power output used a comparable laser power meter as the participant in terms of accuracy, and that this discrepancy is ultimately a limitation in the precision of this device. These data demonstrate that the absolute laser power accuracy can vary over the entire range of its output even upon initial installation of the AM system.

2.2. Large facility – many AM systems

The next example comes from a large AM facility where nine AM systems of the same make and model were measured. Each system had a single laser with a maximum output of 400 W. Here, technicians assess laser power output, which is recorded weekly. This participant had two laser power meters, which were sent to the power meter manufacturer for recalibration every 18 months on an alternating schedule.

Fig. 2 compares the results of these identical systems (all are of the same model number). Measurements from individual systems are given by open symbols and closed symbols are the average values. Fig. 2a. shows the machine setting discrepancy relative to NIST values (horizontal lines with dashed lines showing absolute uncertainty). Fig. 2b. shows the discrepancy of the participant's measurements with their meter. The error bars are the standard deviation of the 9 systems measured. Across the entire range of measured power, the average machine setting has a near zero discrepancy, with only a couple of individual machines being outside the uncertainty of the NIST device. However, the variability across the machines is relatively large at 2.9 – 4.6 %. The machine setting is determined by a technician during the initial installation and at regular servicing intervals, whereby his power meter is used to create a laser output calibration file. It is possible that this machine-to-machine variability is acceptable, but this largely depends on the type of material and parts being printed. For more difficult-to-print materials like copper and aluminum alloys, a process window of less than 1 % may be desirable meaning that the laser power output variability across machines could become an issue.

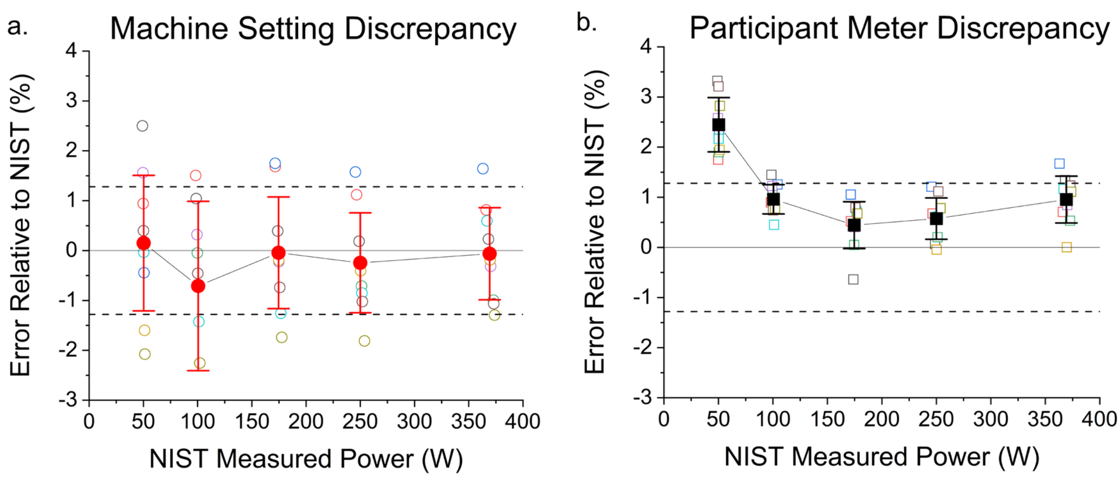

Fig. 2: Laser power discrepancy between NIST measured results and the machine setting (a.) and the participant's power meter (b.). The open symbols are from individual AM machines, nine in total, and the closed symbols are the average of all machines. The error bars are the standard deviation of all 9 measurements. The participant's power meter had a stated uncertainty of 4.5 %.

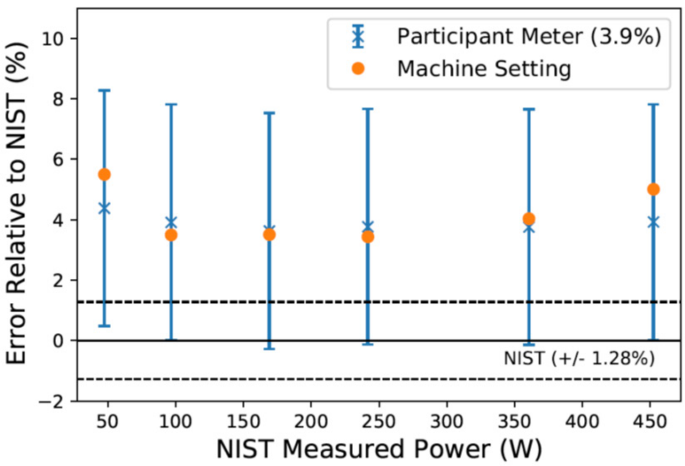

Fig. 3: Laser power relative to the NIST measured power of the participant's power meter and the laser power output programed into the machine ("Machine Setting").

The participant measures laser powers with their power meter that are in reasonable agreement when considering the 4.5 % uncertainty of their device (Fig. 2b.). Interestingly, every AM system measured by the participant exhibits a similar trend with power where the discrepancy is highest at the lowest power, lowest at 175 W, and then gradually increases with laser power. This trend is attributable to the calibration of the participant's power meter relative to the NIST device.

2.3. Routine AM system calibration

The last example comes from a large manufacturing participant who operates dozens of AM systems more-or-less continuously. Of these, NIST was able to measure only one system. Laser power is a routine part of the participant's quality control as is the recalibration of their power measurement device. The participant recalibrates the instrument configuration file as necessary such that the machine setting matches that measured on its power meter. Fig. 3 shows the results from their facility.

As can be seen in Fig. 3, the machine setting closely matches the laser power of their power meter. This is unsurprising given their frequent recalibration procedure. However, there is a discrepancy of about 4 % between these measurements and that measured by NIST, which is close to the uncertainty limit of their device. This is a case where the participant appears to have a mature laser power quality control protocol, but they are ultimately limited to 4 % accuracy of their device. If this participant wishes to have a tighter tolerance on their laser power output, reducing the uncertainty of their power meter would accomplish this.

3. Conclusions

The NIST AM round robin study has been designed to assess the accuracy with which laser power is being delivered on the manufacturing shop floor. This study is ongoing, but we have presented several examples from our initial findings. Ultimately, the accuracy of laser power output is limited by the accuracy of the commercial laser power meter used by either the technician during servicing or the user during routine calibration. We have found that laser power delivered by AM systems agrees with the NIST power meter to within the 5 % uncertainty typical of commercial power meters. Participants have expressed a need for greater process control in their production, but these reports are largely anecdotal. During the course of this round robin, we have also found that not all AM system manufacturers readily allow the user the ability to measure laser power either at all, or without a proprietary access key. Hopefully this will change and moving forward we hope that AM operators will not be limited by this lack of access.

Acknowledgements

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