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Additive manufacturing: The need to get the laser beam right

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Abstract

Is additive manufacturing ready for mass-production? The answer really boils down to reproducibility. When it comes to selective laser melting, the constancy of the laser parameters is of great importance. Both the manufacturers of the laser systems and the users thereof should be aware of the quality of the focused beam. As measuring a high power laser beam in the limited space of a production chamber is a challenge, new measurement technology had to be developed. Today, different technologies are available to measure the focused beam quickly and cost-effectively within the process.

Keywords: additive manufacturing; selective laser manufacturing; laser beam parameters; non-contact measurement;, Rayleigh scattering; reproducibility; quality; troubleshooting

1. Challenges of laser-based metal powder bed fusion systems

Most laser-based metal powder bed fusion systems (LPBF) – frequently referred to as metal AM systems – rely on much the same beam delivery concept. In most cases, the beam as it exits the laser will not (yet) have the size, shape or intensity profile needed for the application. Starting at the fiber laser source with the beam delivery fiber and beam expansion optics, there follows either a 2- or a 3-axis system. The laser beam will be expanded and may be shaped, it can be steered by galvanometer mirror systems, and it will travel through several transmissive optics before reaching the process. In short, there are many opportunities along the way for the beam to be inadvertently modified before it ever reaches the working plane.

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Optics and mirrors gradually absorb more laser light as they degrade, causing the delivered laser power to decrease over time. Some wavelengths of light are very hard on system components. Thermal effects caused by absorption will change the size or location of the focused spot. This is known as ‘thermal lensing’ and leads to ‘focal shift’. If the laser focuses before it reaches the work plane, the power density is reduced because the beam begins expanding again before it hits the work surface. Furthermore, high power densities can generate a plasma in the focal spot region that influences the beam quality. If the laser focuses beyond the work plane, the power density again suffers.

These changes have always had a large impact on the manufactured parts, but as the industry hastens toward to mass production, the stability of the laser parameters grows ever more important. Leaving material-related and work strategy questions aside, the crucial issue in terms of achieving reproducibility is what kind of influence the optical components with their various coatings, power densities and alignment will exert on the production process, and how the interplay thereof can be managed to achieve constant beam parameters.

As if the challenge of setting up one laser beam path and managing the involved optics were not enough, larger parts are typically built using *multi*-laser systems. The basic structure of the entire beam delivery is replicated up to four times in one LPBF system, working in a stitching mode. Not only do the individual laser beams need to be aligned precisely to achieve durable, high quality parts, they also must be matched to near-identical performance – a Herculean task.

To ensure that the process remains consistent over time, regular measurement of the laser beam is necessary to control performance and to:

- Minimize the risk of bad parts – before starting costly production of large parts or series
- Assure reproducible and traceable product quality
- Increase the efficiency of the processes to keep the piece price as low as possible
- Maximize machine utilization time – avoid unplanned stoppages, shorten maintenance downtimes
- Optimize resource utilization – energy, process gases, powder

2. Key laser parameters and their measurement

As with every measurement task, there are different philosophies on what to measure and how to measure it. In the past few years, significant process has been made in terms of available measurement technologies that are suitable for different use cases in additive manufacturing. Essential parameters measured in LPBF applications are:

- Power and energy at the focused spot
- Spatial intensity distribution
- Location of the focused spot
- Power density
- Beam profile
- Divergence
- And, very important: the stability of each of these parameters over time

When it comes to choosing a suitable measurement technology that can be used in production lines, three constraints need to be taken into account: physical space, time and laser power. As the measurements usually need to be taken within the working chamber, measurement devices cannot be large or complicated to use. If the device is quickly positioned, easy to align, and poses little risk of damaging the equipment, it is more likely to be accepted by users for frequent measurements. Also, a short measurement time is itself important, because this is the prerequisite to integrating regular measurements directly into the production process. Moreover, LPBF processes often use laser systems in a power range between several hundred Watts to over 1kW; some measurement technologies cannot handle these powers without water cooling – a highly sensitive topic in closed LPBF work chambers.

2.1. Measurement technologies for lasers in LPBF

2.1.1. Power and energy measurement

The first step in knowing whether a laser beam is working according to specifications is to measure the power of the laser beam. Traditionally, power measurements are performed using different types of sensor heads combined with meters or PC interfaces. Designed for use in closed AM production chambers, new compact industrial power meters such as the Ophir® Ariel™ work as standalone systems. By measuring the energy of a short time exposure, laser powers up to 8 kW can be read without further cooling. Additionally, industrial power meters are dustproof, compact and easy to transport. Communication options include Bluetooth® for transmitting readings from inside a closed machine to a mobile phone or laptop, as well as a USB-C interface. Alternatively, the data can be directly stored in an internal memory.

Fig. 1. Industrial power meters can be used even in very small work chambers (Picture in cooperation with Leibniz Institute for Solid State and Materials Research Dresden)

2.1.2. Power position sensors

Then there are the quadrant sensors or power position sensors (PPS), which measure not only the power but also the position and size of the beam, going a step further than conventional power gauges. When the sensor is positioned centrally and moved vertically, the beam position should show no movement at all. Any change in the measured beam position indicates an offset in the deflection head or a misalignment in the beam path. To a certain extent, this sensor technology can also be used to determine the accuracy of the beam adjustment in the peripheral areas of the building plane – in terms of both power and beam position.

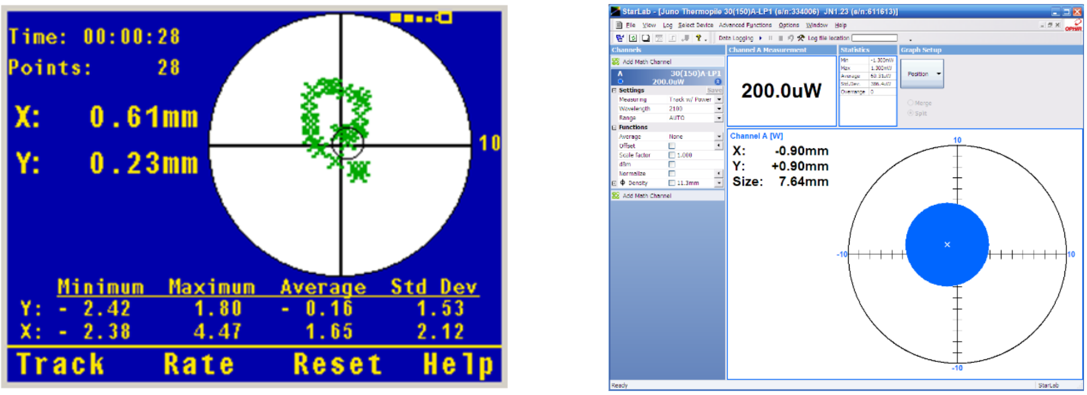

Fig. 2. Measurements taken with PPS sensors can provide first indications of the status of a laser-based system

2.1.3. Camera-based beam profiling with beam attenuation

Recently, a third option for measuring the high-power beams in LPBF processes has opened up: Thanks to a newly developed beam attenuation technology, it is now possible to use a lower-cost CCD beam profiler (a well-known technology for low power) to measure the laser beam in the work chamber. This approach can be seen in the new Ophir LBS-300 HP-NIR beam attenuation system, which was designed for focused-spot beam analyzers that combines dual sampling optics and neutral density filters for beam attenuation before the focused spot reaches the camera. This innovative beam splitter is designed for high-power lasers and employs newly engineered sampling optics that allow measurement of NIR (1,000-1,100 nm) focused or collimated laser beams profiles up to 5kW or 15MW/cm^2. With this technology, a cost-effective system is now available that provides the usual 2D and 3D beam profiles, along with the capability for fast measurements of both an image integrated over a certain period of time, and of the full beam profile with dynamic changes at video rate.

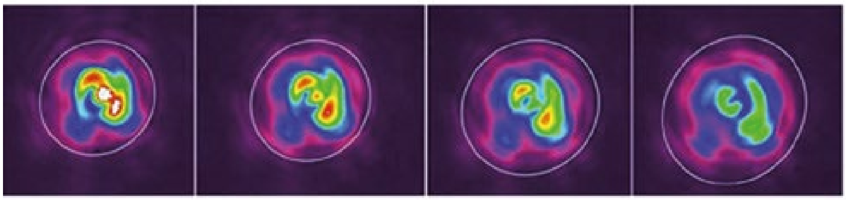

Fig. 3. Beam profiles delivered by a camera-based beam profiler

2.1.4. Non-contact measurement

The fourth approach to measuring the laser beam within the work chamber employs a non-contact measurement technology based on the Rayleigh scattering of the laser beam. Developed by MKS Instruments, this technology developed for measuring high-power laser beams in multiple applications, has been further enhanced for use in additive manufacturing systems and built into the Ophir BeamWatch® AM measurement device. It allows for the measurement of beam position and angle of incidence, focal spot size, position and quality parameters such as M^2 and beam caustic – all in real-time. The user can easily determine when the beam is aligned and in focus, providing more consistent material behavior.

The advantages of non-contact laser beam measurement are particularly important at higher power densities of more than 2 MW/cm^2, as currently required in LPBM. Because the instrument can record power up of to 1 kW for as long as two minutes without needing active cooling, it can be used in R&D as well as in production and service. The non-contact measurement technology guarantees that there is no wear and tear, as the beam never touches the device. And the device's centering 10 mm dowel pin hole enables fast alignment in the working chamber, so reproducible measurements can be achieved easily. As the measurement itself only takes fractions of a second, the focus shift can be measured, delivering a realistic picture of the process. Traditional measurement devices are much slower and thus only purport to show stable processes – when in fact, they are simply not able to detect focus shift at all.

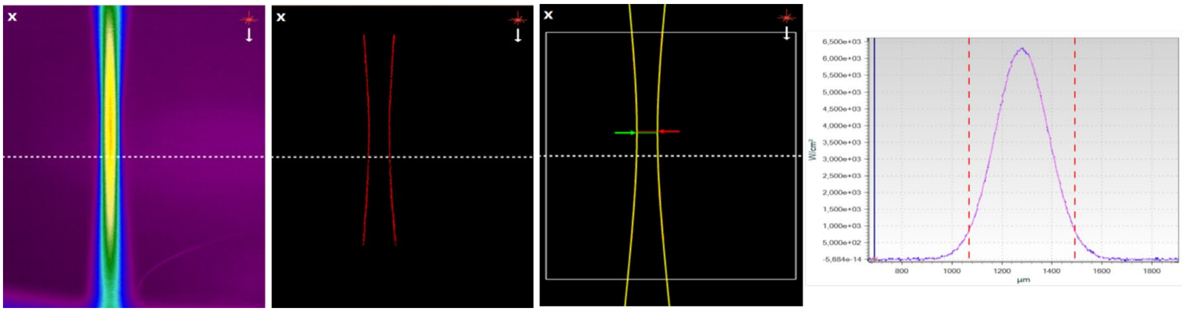

Fig. 4. Different views based on measuring 2048 beam profiles at video rate: A, an image of the Rayleigh scattering; B, the measured points; C, the ISO curve fit; D, a 1D-profile (left to right)

3. Practical use cases

More and more end users of LBPF systems are realizing the necessity to measure the laser to ensure stable and reliable processes. Different measurement technologies offer suitable options for most use cases. To quickly detect a trend, measuring the power of the laser beam with an industrial power meter or using PPS sensors usually serves well as a first indicator. When it comes to more detailed and complex building jobs, measurement technologies such as camera-based beam profiling or non-contact measurement of the beam are the technology of choice. The combination of new attenuation optics and CCD camera delivers a relatively low price tag along with a compact and lightweight design that facilitates frequent performance monitoring. Keeping an eye on the trend lines of power density not only enables narrower process windows, it also permits operation of the laser system closer to its optimum specifications. When it comes to regularly measuring the performance of the laser in the working chamber, a measurement device based on the non-contact measurement technology offers many advantages.

3.1. Non-contact measurement to detect focal shift, a use case

Often, quality issues are what lead to the measurement of the laser beam. In this case (see Figure 5), a non-contact beam profiler was used. When the measurement revealed a significant focus shift, the experts suspected either some improperly cooled optical parts or a damaged lens or protective window. Even though at first glance the protective window looked fine, after cleaning it the quality issues were resolved.

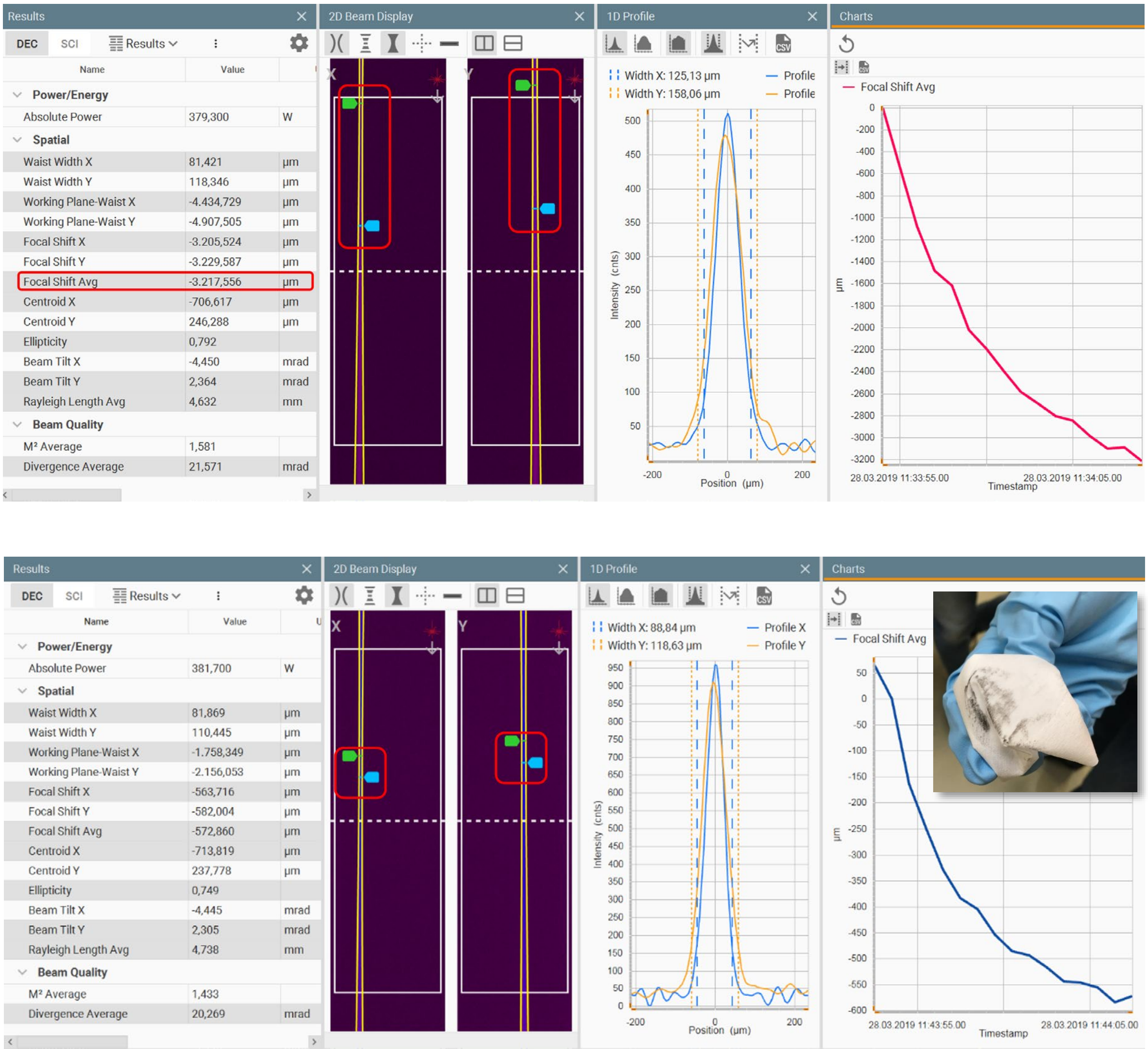

Fig. 5. Non-contact beam profiling detected a focus shift; quality issues were then quickly resolved

3.2. Non-contact measurement to detect surface issues, a use case

In additive manufacturing, material surface and strength are key quality characteristics. Because even the smallest issue will result in scrap, it needs to be resolved quickly to conserve time and resources. Measuring the laser's caustic can reveal multiple deviations of the laser beam, see Figure 6. Here, the position of the beam's focus had changed in both the x and y directions, so the distribution of the beam was no longer Gaussian: Secondary maxima had led to a donut shape and caused low production quality (TEM10 instead of TEM00). Due to the enlarged focal spot, the power density was reduced, which resulted in porosity and insufficient strength in the produced part.

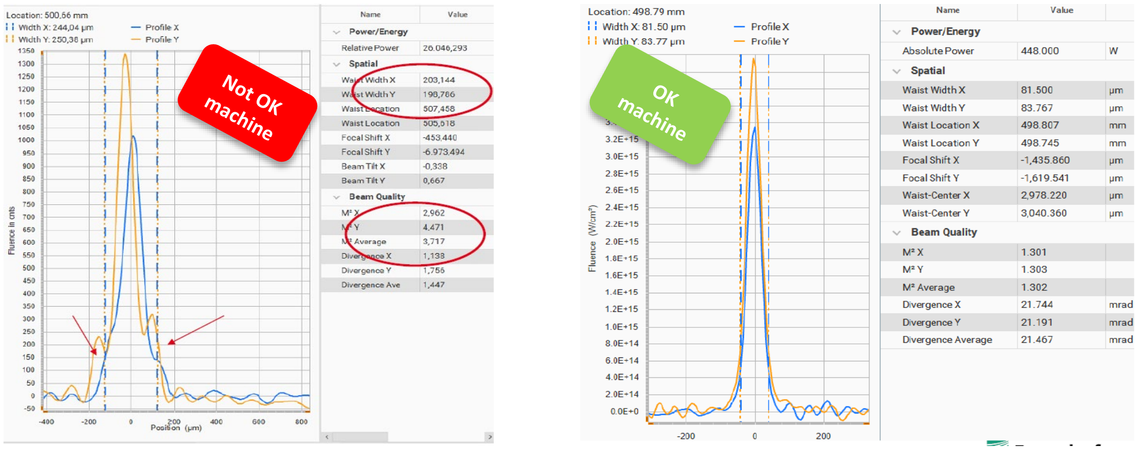

Fig. 6. Measuring the beam caustic delivers valuable insights for troubleshooting (Measurements taken in cooperation with Fraunhofer Institute IAPT)

4. Conclusion

Beyond material costs, one of the most significant challenges faced by additive manufacturing is ensuring the reproducibility of a finished part's dimensional accuracy and strength and the quality of its surface. While some costs can be readily controlled, for example through specially tuned engineering of the finished parts, as long as laser beam parameters are not measured regularly in short intervals, reproducibility will remain the industry's Achilles heel. Online monitoring with "closed loop" control in the process would be ideal. However, even such a system cannot compensate for dirty or misaligned optics. By using currently available beam caustic measurement, the operator can gain deeper insights into the performance and maintenance status of the LPBF system. Even simple power measurements can detect increasing absorption losses due to contamination or aging of the optics over time. With just this trend analysis, a system operator can develop a better understanding of the process, enabling fact-based decisions about upcoming service tasks or risk assessments for the next construction job. With a clear measurement strategy and a careful documentation of the results, process windows can be significantly narrowed. Deviations between components can thus be reduced, and good parts can be produced in a controlled manner. The right choice of measuring equipment is important. If a focused laser beam is to be measured frequently, the measuring device itself must be protected from the high power densities involved; however, damage can be prevented by using non-contact measurement principles for beam diagnostics. The results of such measurements are thus unambiguous, require no interpretation and will finally pave the way to mass-production in additive manufacturing.