Sensor Fusion Enables Comprehensive Analysis of Laser Processing in Additive Manufacturing

By Kevin Kirkham, Senior Manager, Product Development, Ophir

Sensor: "A device that detects or measures a physical property and records, indicates, or otherwise responds to it." A sensor is a device that detects a physical quantity and responds by transmitting a signal.

Fusion: "The process or result of joining two or more things together to form a single entity." A blending, amalgamation, joining, marrying, bonding, merging, melding, or synthesis of materials or information to realize a sum that is greater than their parts. In this case, the data from numerous sensors are fused to create a more complete understanding of the laser-enabled process.

New laser processes, including such additive manufacturing (AM) techniques as Selective Laser Sintering (SLS) and Selective Laser Melting (SLM), require consistent energy be delivered to the material that is to be transformed. Successful outcomes require the power density distribution of the laser beam, as it is delivered to the work, to be symmetrical, uniform, and stable. Most laser applications require the beam spot size and intensity to be maintained within a finite acceptance window. In many cases, laser parameters must be measured to be certain the requirement for consistent, stable, and correct laser power density is met.

But just as Icarus was warned not to fly too low should the dampness of the sea damage his wings, nor fly too high for the sun would melt the wax that secured the feathers that formed his wings, laser sintering applications must monitor the power density of the presented laser beam so the power density is neither too "hot" nor too "cold" for successful material modification.

How do we know the laser is delivering exactly the beam that's needed? Most commercially available laser power / energy measurement products offer traceability of the calibration of both the sensor and sensor interface or meter. The US-based National Institute of Standards and Technology (NIST) and the German-based Physicalisch-Technische Bundesanstalt (PTB) provide laser power sensor calibration services. These government organizations trace their calibrations to a standard based on calorimeter measurements.

Power and Energy Sensor Traceability and the Uncertainty Budget

A detailed description of typical laser power and energy calibration errors is available from Ophir Photonics. This paper discusses the key factors of wavelength, linearity, and uniformity, as well as how these factors affect sensor accuracy and how to minimize laser intensity measurement errors.

Commercially available products that measure some of the key SLS parameters include laser power meters, laser beam profiling systems, and products that combine both of these products into one device.

CCD and CMOS silicon array sensors are used to produce quantitative, 2D images of the energy distribution. These systems provide accurate measurements of the beam size, beam location (Centroid), and how energy is distributed within the focused spot (beam profile).

Digital camera measurement systems provide a spatially accurate intensity map of the laser's output. By measuring the total laser power and associating that power measurement with the beam profile taken of the same beam, an accurate, cross-sectional power density map of the laser beam is possible.

The absolute accuracy of camera based beam profiling systems is limited by: detector linearity, spatial uniformity, modulation transfer function (MTF) or spatial sampling frequency of the imaging system, and temporal resolution (temporal sampling frequency). Scanning slit and other types of laser beam profile measurement devices are also used to measure the energy distribution within high power (>1MW/cm^2) focused laser spots.

Beam Profiler Traceability

NIST does not currently offer calibration services of beam profile measurement equipment. While this service has been offered in the past, it is not currently available.

Most beam profile sensors can be used to help create a meaningful map of the irradiance of the working laser beam, if an accurate power or energy measurement of the beam is available. Not all focused beams are alike. Some beams focus to very clean, super-Gaussian distribution, while other focused beams relay an image of the fiber optic to the work surface. Some beams are designed to deliver a uniform or Top Hat distribution at the presentation plane of the system. Focused beams can be severely distorted to the point that the task at hand is in jeopardy.

Understanding the energy distribution within your focused, working beam may be the difference between success and failure. Areas of the beam that exceed the operation power density threshold will do work. While areas of the beam that do not exceed the working power density of the application may harm the process by coupling unwanted heat into the material to be modified.

Any areas where power density greatly exceeds the working threshold may damage the material or cause weakness in the structure.

Insufficient power density may cause the joining of layers to be incomplete which can introduce weakness or even voids into the build.

The range of power densities between the minimum effective irradiance and the irradiance that causes damage to the build, or irradiance that is insufficient to bond the new layer to the previously build structures, is the operational range of the additive manufacturing system. The beam profile and delivered laser power should be measured to assure the process is robust and to avoid damaging or insufficient irradiance levels.

AM Diagnostic Products

While in its infancy, numerous diagnostic products and procedures have been developed to help to assure all variables are optimized for the best possible additive manufacturing outcomes. Commercially available products include:

- **Powder Analysis:** Powder size, particle shape, particle size distribution, chemistry, and powder density all impact the integrity and metallurgical properties of the additive manufacturing build. Laser diffraction technology can be used to analyze and understand the particle size and particle size distribution of powder. Electron scanning microscopy can evaluate the surface and internal morphology. X-ray fluorescence spectroscopy can analyze the chemical composition of the powder before and after processing.
- **Thermal Image Analysis:** Some additive manufacturing systems offer a thermal analysis option as a way to monitor the process. There have been some efforts to use the irradiated spectrum of the process as a diagnostic indicator.

Laser Beam Profile and Optical Power Analysis

Laser beam profiling products have been modified for analyzing SLS/SLM lasers. The challenges include but are not limited to:

1) The very high power density of the AM working laser beam. Power densities of greater than 2MW/cm^2 are typical.
2) Rapid changes in the delivered beam require measurement update rates sufficient to capture these changes. Measurement cycle times must be 10mS or less. Otherwise, small changes in the characteristics of the delivered laser may be missed.
3) The SLS/SLM environment may also provide environmental challenges such as powder contamination of the optics, incompatible purge gasses, or elevated temperature build environments.

New technologies are being used to solve the challenge of understanding the laser performance as it impacts AM processes. Rayleigh scatter is one new method used to image the focused beam without interacting with or modifying the delivered laser energy in any way. In the case of the Ophir BeamWatch non-contact beam profiling system, Rayleigh scatter allows measurement of the focused region of the beam (caustic), at up to 100 times per second. This permits the additive manufacturer to understand and measure the focal shift of the delivered beam as the delivery optics thermalize and reach operating temperatures.

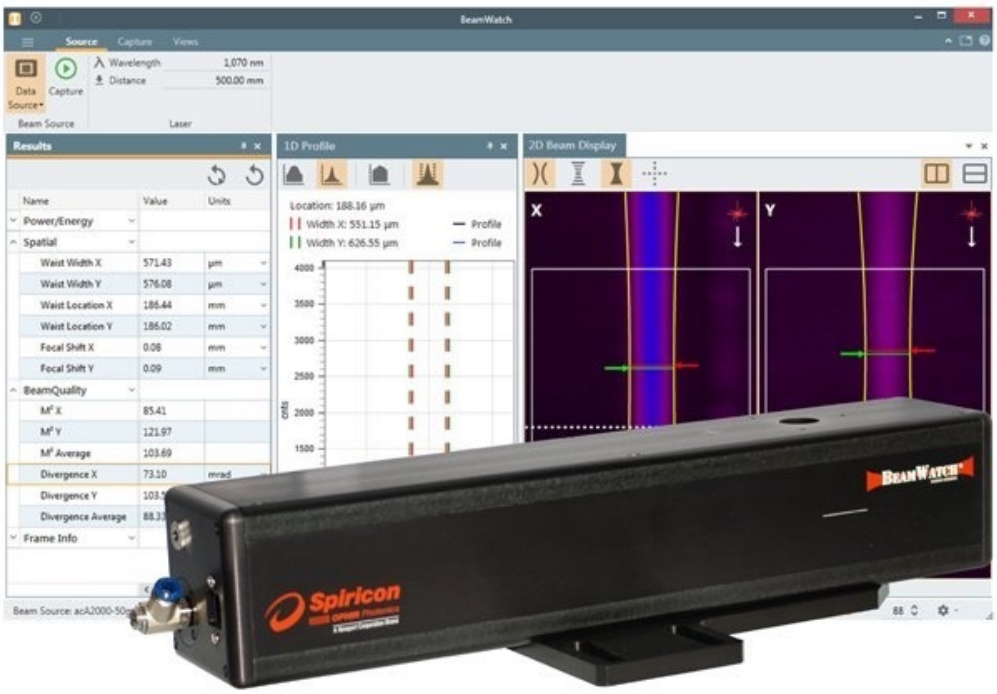


Figure 1. The BeamWatch® non-contact beam profiling system uses Rayleigh scatter to measure high power lasers.

BeamWatch also permits real-time measurements of the laser's M^2 (beam propagation ratio), K ($1/M^2$), and BPP (beam parameter product). These measurements define the applicability of the laser for the task at hand.

Camera-based beam profiling systems are coupled with a power meter to provide real-time beam profile measurements that are “calibrated” with the power measurement to create a power density map of the working spot that is delivered to the work plane.

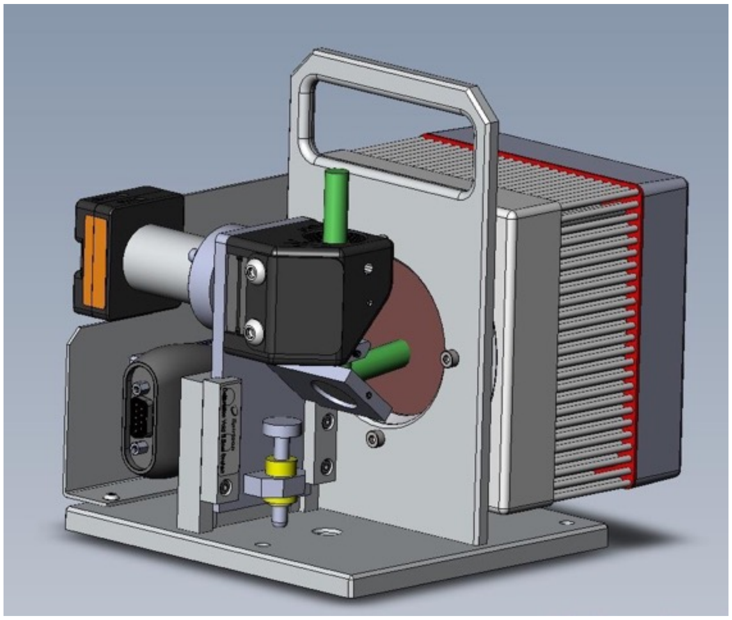


Figure 2. The BeamCheck™ system for additive manufacturing applications measures the laser's focal spot size, power, and power density at the build plane.

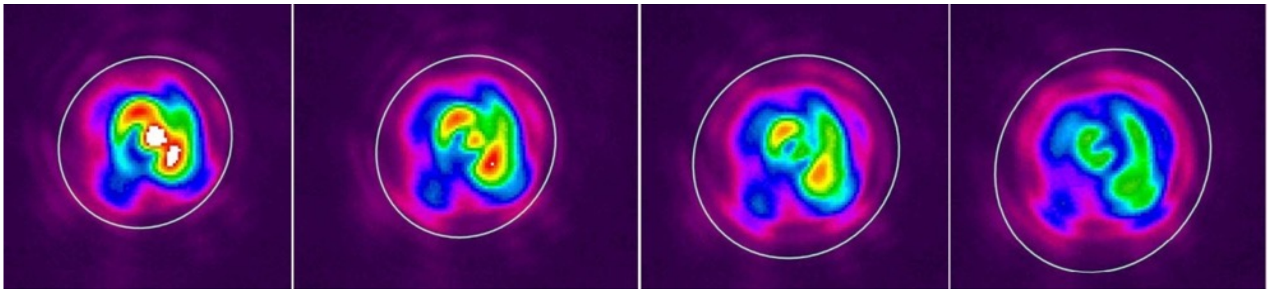
Spatial resolution of scientific grade CCD and CMOS camera sensors is finite and forms the lower limit of measurable spot sizes. A minimum of 10 pixels are needed to obtain meaningful beam width measurements. Beam profiling camera systems typically offer pixel pitches from 3.75um to 10um. The active area of a beam profile sensor should be a minimum of ~1.5 times of the 1/e^2 width of the beam being measured. Currently available sensors offer active areas from 6.5 x 5mm to over 35 x 24mm.

Be careful to use the correct beam profile sensor for the laser wavelength. CCD and CMOS cameras operate in the 200 to 1100nm range. Due to the relative insensitivity of silicon in the near-IR, some camera sensors may not be appropriate for the longer wavelengths of Nd:YAG and fiber lasers.

With power densities in excess of 1MW/cm^2, great care must be taken to obtain accurate measurements of the working laser beam. Dirty or damaged optics can severely distort the beam profile and may also cause errors in the power/energy measurement. High power laser sensors are expected to survive power densities of 10kW/cm^2 without damage, so it is important to keep the optical surface of these sensors as clean as possible. Dirt and debris can reduce the lifetime and accuracy of these products. A blast of forced air or a careful cleaning with distilled water may be occasionally required. Be careful to follow the manufacturer’s directions.

Combining the total integrated power measurement of the laser beam with a time relevant beam profile measurement enables the acquisition of power density maps of successful builds that can be archived and compared to subsequent profiles. Most beam profiling systems provide capabilities to establish pass / fail windows for all of the laser performance parameters critical to successful builds. By measuring the powder and obtaining a power density map of the beam that is interacting with the powder, an informed assessment of the goodness of the process can be made. Any variations from historic performance can be compared to known additive manufacturing norms.

By combining beam profile images with measurements of the total power delivered to the powder bed, a complete representation of the energy density profile of the laser beam can be understood. With a series of beam profiles taken every 20mS, beginning with a cold start, the effects of thermal equalization of the beam delivery optics can be observed. As you can see in Figure 3, as the delivery system heats up the beam is spread slightly. The consequences of this slight enlargement of the beam can clearly be seen in the computed peak and average power within the beam.



Diameter	0.43	0.48	0.52	0.55	mm
Power	288	289	292	299	Watts
Peak	3.97 x 10^5	3.19 x 10^5	3.23 x 10^5	2.5 x 10^5	Watts/cm^2
Average	1.36 x 10^5	1.11 x 10^5	1.10 x 10^5	8.6 x 10^4	Watts/cm^2

Figure 3. Beam profile measurements of total power delivered to the powder bed over time.

Optical windows are used in most laser sintering machines to provide a barrier between the build chamber and the laser and delivery optics. Condensation from the outgassing of some polymers collects on these windows and over time obscures the beam leading to lower power and a broadening of the delivered focused spot. Both of these changes to the delivered beam reduce the amount of energy that is available to the process of melting the polymer. This can lead to incompletely formed structures with inconsistent mechanical properties.

Conclusion

Hybrid systems that employ multiple sensors provide meaningful insight into laser-powered additive manufacturing processes. Laser power/energy data combined with the laser beam profile provide an unparalleled level of understanding of the SLS /SLM processes. Intensity-calibrated beam profiles of the laser beam at the working plane help establish process norms and then pass/fail tests can alert AM systems operators when laser parameters fall outside of the established performance standards.