Novel Beam Diagnostics Improve Laser Additive Manufacturing

Laser additive manufacturing (LAM) is rapidly becoming an important method for the fabrication of both prototype and production metal parts. However, the technology is really just in its infancy, and significant work still needs to be done in the development of new materials and in understanding how various process parameters affect results. In particular, LAM methods typically have a relatively small process window for laser performance, where minor changes in beam and scanning parameters can significantly affect results quality. This document examines the need for laser beam characterization to deliver optimum results, and then shows how a new beam monitoring technology, developed by Haas Laser Technologies and Coherent (in cooperation with Pennsylvania State University's Center for Innovative Materials Processing through Direct Digital Deposition), enables rapid measurements in laser-based 3D manufacturing systems. Ultimately, this technology will allow beam issues to be identified and corrected before they seriously impact the quality of parts produced using LAM.

LAM Basics

Demanding applications for multi-watt CW green lasers are negatively impacted by fluctuations (noise) in the output beam power. In many solid-state lasers based on neodymium-doped crystals, fibers and disks, the minimum achievable noise is often limited by so-called Most traditional machining techniques are subtractive. That is, they selectively remove material from a substrate to create the desired shape. Additive manufacturing methods work the opposite way, building up a part layer-by-layer.

There are two basic categories of laser additive manufacturing techniques for producing metal parts; directed energy deposition (DED) and powder bed fusion (PBF). In DED, metallic powder is fed into a moving laser beam and is melted and deposited onto the surface to create each layer. Typically, both the beam and powder feed mechanism are moved over the part in unison to create the desired shape.

DED commonly utilizes relatively high power, near infrared, fiber delivered lasers, in the 500W to 10 kW range. These can be ytterbium fiber lasers, Nd:YAG lasers or direct diodes. Spot diameters at the work surface range from 500 µm to 5 mm, depending upon power. DED is not a high precision process. Rather, some machining is usually required after deposition in order to obtain the finished part dimensions.

Powder bed fusion (PBF), the primary LAM technique for producing finished parts, is essentially a form of 3D printing which uses metallic powders and a laser source to melt them. PBF delivers parts that are essentially at their finished dimensions, with accuracies at the micron level.

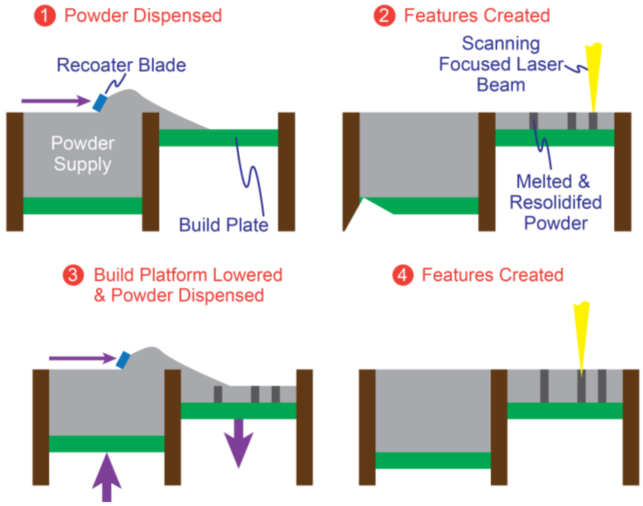

Figure1 *The basics steps of PBF.*

In PBF, a layer of metal powder of about 20 µm to 60 µm in thickness is first spread evenly with a "recoater blade" over a "build plate," which is a platform which can be moved vertically. Then the laser is scanned over the powder to selectively melt and resolidify it in the desired pattern for that layer. After a layer is finished, the powder bed is lowered an amount equivalent to the thickness of the layer, and a new layer of powder is spread over it. The laser writes that layer, and the process is iterated until completion. At the very end, the remaining, unmelted powder is removed to reveal the finished part.

PBF usually employs near-IR ytterbium fiber lasers in the 200W to 500W power range. These are scanned in two dimensions (x and y), and focused with a high quality, f-theta scan lens to achieve a spot size in the 100 µm range. This combination of power and spot size easily produces sufficient fluence to rapidly melt metal powders. In fact, it's important that the power density is not so high as to cut or drill the build plate, or to penetrate too far into the metal powder. Optimally, the laser should completely melt through the new layer of powder and a small amount of the previous layer in order to completely fuse the two and produce uniform material properties throughout the entire part.

Current LAM Applications

The flexibility and speed of 3D printing with polymer materials have made it a widely used tool for engineering and prototyping purposes. The ability to work with metals and deliver finished parts which have robust mechanical properties extends PBF into a useful technique for the fabrication of actual production parts in a variety of industries, including aerospace, dentistry, motor racing and even jewelry.

Specifically, PBF is most effectively employed for the production of high value, critical parts which are both mechanically intricate and costly to produce using other methods. Examples would be shapes having complex curves, and internal holes and channels.

A standout example of PBF is production of the fuel nozzle for the Leap jet engine at GE Aviation. According to GE Aviation, this single part, created with internal support structures and cooling pathways, replaces a machined assembly consisting of 18 separate pieces. The LAM produced part is 25% lighter and about five times more durable than the machined equivalent. Since each Leap engine incorporates 19 of these nozzles, this weight reduction results in a noticeable fuel savings.

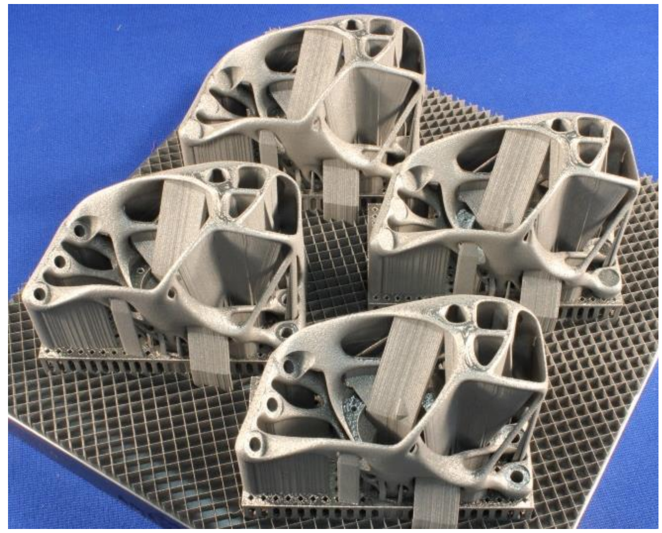

Figure 2 *PBF produced sensor brackets. The complex shape, which optimizes mechanical stability, would be difficult to achieve using traditional manufacturing methods. Photo courtesy of CIMP-3D at the Pennsylvania State University and Materials Science Corporation.*

Technology Challenges

While there are already a number of sophisticated, turnkey PBF systems commercially available, these don't provide the intimate level of process control necessary for success in some applications. For example, there are various considerations related to part orientation during fabrication that can cause difficulties with the deposition process, or lead to undesirable stress characteristics in the finished product. These can't always be completely addressed with current commercial systems.

There are also material related cost challenges with commercial LAM systems. For instance, while these systems work with a variety of powders, including aluminum, cobalt, titanium, stainless steel and nickel alloys, each one requires a different set of deposition parameters. In many instances, these parameters are proprietary to the machine supplier, and must typically be purchased individually at a price in the $10,000 to $20,000 range. And, since they are directly downloaded into the machine, the user still may not have access to all the parameters necessary to optimize or modify the process for their particular needs.

In terms of materials, it is also important to note that the powders currently in use are essentially alloys that were developed for traditional, wrought metal manufacturing techniques (which usually involves multiple steps of melting, forming and subsequent thermal processing). And they don't yield the same, desirable, bulk physical properties, such as tensile strength, when just rapidly melted and resolidified during LAM. Thus, an important area of research is the development of new materials which will deliver improved physical characteristics specifically when utilized in LAM. In fact, this is critical to expanding the utility of the technology.

As a result of these factors, there are numerous research groups and end users who wish to modify existing systems or build their own LAM systems which will enable them to completely investigate and control every process parameter. This enables improved results and the development of a more clearly deterministic process.

Beam Metrology Needs

While there are well over 100 process parameters specified in the software of most LAM systems, some of the most critical ones, over which the operator has little control, have to do with the power, shape and size of the focused laser beam; these ultimately determine the dimensions of created features and the physical characteristics of the material. This makes beam metrology particularly critical to the process.

Beam variations occur due to several factors. First, there may be some inherent power drift in the laser output. Next, the output power levels used in PBF are sufficient to cause thermal lensing in the beam delivery optics, which can change the beam waist position, as well as distort the spot shape. Also, since the beam is scanned over a wide field of view, the spot shape will usually be elongated at the edges of the field.

These considerations lead to a direct need to measure laser power, spot size, mode details and beam waist location within PBF systems. In particular, it's necessary to acquire these measurements after the final f-theta scan lens, rather than at some intermediate point in the optical system, so that the beam has already encountered all possible factors that might affect it. Furthermore, it's ultimately desirable to develop a rapid measurement method, so that power density and beam waist location could be measured between each layer write cycle, without significantly slowing deposition down. This would enable any necessary corrections to be made on the fly to laser output. Alternately, it could automatically abort a build cycle, which can be in the 20 to 60 hour range for PBF systems with about 10" x 10" build platforms, if the process has gone significantly off-track.

Novel Beam Metrology Solutions

Unfortunately, there are limitations with the traditional techniques for measuring laser mode, waist location and power that compromise their use in this application. Specifically, laser mode measuring instrumentation usually operates by sequentially scanning a slit or aperture across the laser beam at multiple distances from the source. This allows a full picture of the propagation characteristics (mode) to be acquired, and the precise beam waist location to be identified. However, this type of instrumentation is relatively slow and bulky.

Similarly, direct power measurement of high power lasers has traditionally been accomplished with thermopile detectors. While this technology can handle the high average laser power in LAM systems, it would be too slow (a measurement usually takes several seconds) to achieve in-process monitoring between each powder layer during part fabrication.

Now, a novel system from Haas Laser Technologies addresses both these issues. It can deliver very rapid measurements of beam mode, and nearly instantaneous power for both CW and pulsed, high power lasers using PowerMax™-Pro sensing technology from Coherent. Specifically, their Beam Waist Analyzer Camera (BWA-CAM®) measures many laser parameters including the beam waist position, beam size, and M^2 of high power lasers all in a single, fast (less than 1 second) measurement. When combined with a simultaneous fast power reading from the PowerMax-Pro sensor, this allows system software to calculate power density. And, critically, the system is sufficiently compact to enable easy use, or even integration, within the build area of LAM systems.

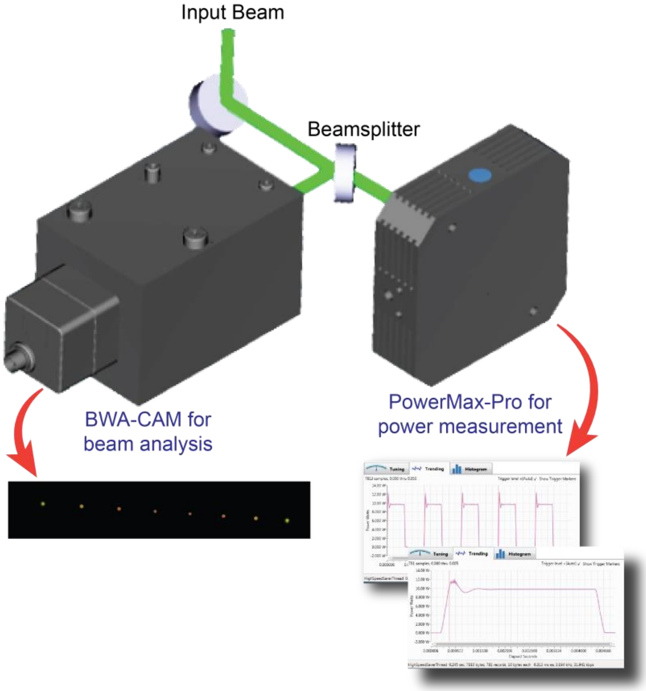

Figure 3 *Combining results from the Haas BWA-CAM and Coherent PowerMax-Pro delivers accurate measurements of laser power density at the work surface, which is the key parameter for PBF.*

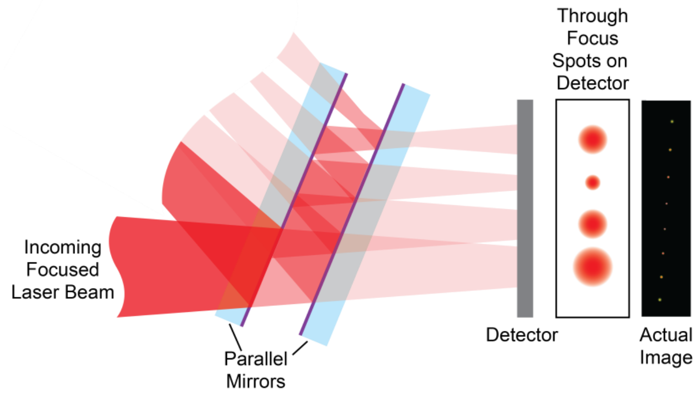

Figure 4 *Simplified schematic of the optical arrangement used in the BWA-CAM to simultaneously image a beam at multiple locations along the optical axis.*

To accomplish this very comprehensive set of measurements, the BWA-CAM acquires several, simultaneous, through-focus images of the laser spot using a clever optical arrangement. Incoming focused light is first attenuated and then directed into a pair of parallel plates, which are tilted with respect to the optical axis. The two interior surfaces of the flats are both coated with a high reflection coating, so that only a small percentage of the light exits the system at each reflection. This transmitted light thus forms a series of spots on an array detector which each show the beam profile at increasing distances along the optical axis. This optical arrangement can be adjusted so that the increment between adjacent spots on the detector represents displacement along the optical axis of 100 µm to 12 mm. System software analyzes this series of spot images to derive all the previously mentioned beam mode and waist location parameters.

In order to directly measure beam power, which is critical for the system to accurately calculate laser power density at the precise location the powder layer is being processed, the system incorporates a Coherent PowerMax-Pro detector. This utilizes a relatively new type of detector technology called a transverse thermoelectric (Patent #9,059,346), first introduced to the market in 2014, which combines the broad wavelength sensitivity, dynamic range and laser damage resistance of a thermopile with the response speed of a semiconductor photodiode (see side bar).

This unique set of characteristics is particularly beneficial in this application. Unlike a photodiode, which saturates at very low light levels, the PowerMax-Pro can measure high laser power directly and in tens of microseconds. This minimizes the need for attenuating optics in the beam path which can be a source of absolute measurement error. Also, in contrast to a photodiode, the response of this detector is highly linear, and the entire power measurement system (detector/electronics/software) is calibrated and NIST-traceable. Thus, it delivers highly accurate, absolute readings of laser power. This is critical to know in order to optimize process parameters, or for analyzing the precise laser/material interaction in the development of new alloys.

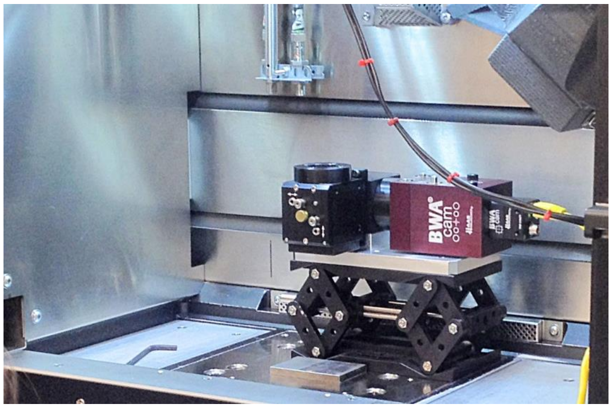

Figure 5. The compact BWA-CAM (2.4" x 2.4" x 3.3"), which provides near instantaneous beam shape, size, focus and power measurement, easily fits in the build platform of most PBF systems. Photo courtesy of the Applied Research Laboratory, Pennsylvania State University.

The high response speed of the PowerMax-Pro also enables it to directly observe pulse shape, rather than simply report average power. This is useful, because deposition quality (e.g. grain size, tensile strength, etc.) is dependent upon peak power, rise time and other pulse parameters. And, even when working with CW lasers, it's important to know how fast the laser reaches full power when powered on.

In conclusion, LAM represents a revolutionary step forward in metal fabrication technology. For this technique to achieve its maximum impact, improvements are necessary in process cost, speed and resultant part quality. High speed, compact and cost effective beam diagnostic tools that deliver beam waist location, beam size, and power density information in less than one second will be a key element in achieving these ends.

Thin Film Thermoelectric Sensor Technology

Traditional Laser Power Sensors

In the past, there were two dominant technologies in use for measuring the average power of lasers. These were thermopiles and semiconductor photodiodes.

Thermopiles have been used for many years as the detector of choice for high power lasers. These detectors operate on the thermoelectric principle in which thermal energy is converted into electrical energy. The typical thermopile consists of a central, light absorbing disk, a series of thermocouples that surround this disk, and an annular heat sink around the ring of thermocouples.

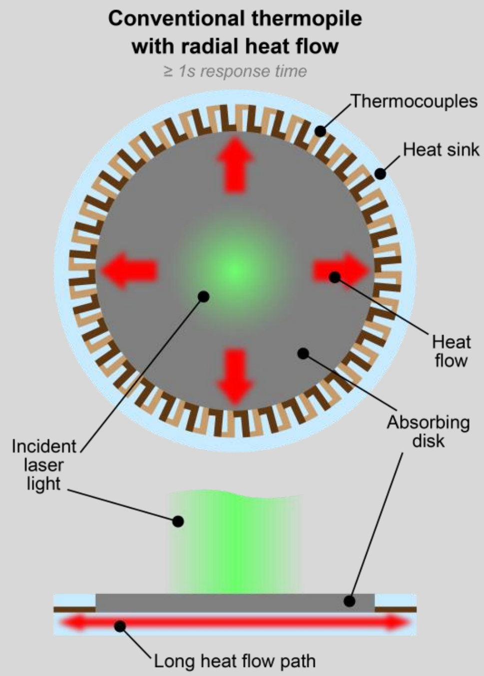

Figure 1 *Construction of a traditional radial thermopile leads to slow measurement speeds.*

In operation, incident laser energy falls on the absorbing disk in the center of the detector and is converted into heat. This disk is typically coated with a material that absorbs light over a very broad wavelength range in order to enhance sensitivity. The heat then flows across the width of the thermopile disk to the heat sink, which is held at a near constant ambient temperature by either air or water cooling. The temperature difference between the absorber and heat sink is converted into an electrical signal by the thermocouples. Calibrated electronics in the meter convert this electrical signal into a laser power reading.

Thermopile sensors have several advantages, including an extremely broad spectral range, an ability to work over a wide range of input powers, high laser damage resistance and uniform spatial response (meaning insensitivity to changes in beam size, position or uniformity). The limitation of the technology is that the transfer of heat across the width of the thermopile disk makes this technology inherently slow. Specifically, it often takes several seconds before the heat flow induced by the laser reaches equilibrium, and the power measurement becomes steady on the display. Physically larger sensors take longer to reach this steady state.

A semiconductor photodiode sensor is essentially a solid state diode (pn junction). Incident laser photons are absorbed by the device and converted into charge carriers (electron and holes). These can be sensed as current or voltage depending upon how the junction is biased. Photodiodes offer high sensitivity, enabling them to detect very low light levels. And several different semiconductor material combinations are available to produce photodiodes that work in the visible, near infrared or far infrared. Photodiodes also have a fast response time, and thus can be useful for looking at pulse shapes. However they saturate above approximately 1 mW/cm², so attenuating filters must be used when operating at higher powers.

Thin Film Thermoelectric Technology

The ideal sensor for embedded power measurement would combine the broad wavelength sensitivity, large dynamic range and high damage resistance of a thermopile, together with the fast response speed of a semiconductor photodiode. Coherent has developed a completely new patented sensor architecture that meets these requirements. It is based on thermoelectric technology, but it is constructed and configured very differently than traditional sensors. Specifically, in this device the heat flows vertically through the detector, and the electrical signal that is generated moves perpendicular to the heat flow.

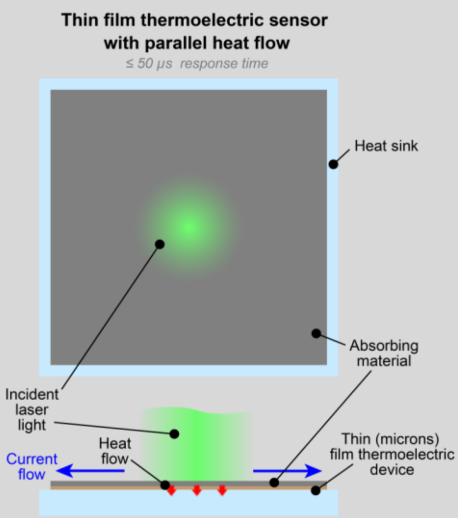

Figure 2 *Basic configuration of a PowerMax-Pro sensor. The short heat flow path results in fast measurement speeds.*

The thermoelectric generating materials used in this sensor are a stack of films which have layer thicknesses on the order of microns, rather than traditional thermocouples.

Incident laser light is absorbed and generates heat which is able to flow very quickly through these thin layers to the heat sink below the detector where it is dissipated. The electrical signal from the thin film layers moves laterally to the edges of the device where it can be measured by tapping into the sensor electrodes.

In contrast to the traditional, radial flow thermopile, which has a sensing time constant value of several seconds, the time constant for the thin film configuration is in the microsecond range. This enables the sensor to provide an essentially instant power measurement without any overshoot. Coherent's first product based on this technology, called the PowerMax-Pro, also preserves the main benefits of the traditional thermopile architecture, namely large active area (30 mm x 30 mm), wide dynamic range (50 mW to 150W), high damage resistance (14 kW/cm²) and broad wavelength range (300 nm to 11 µm).

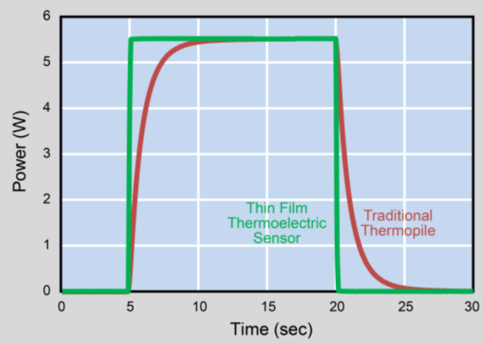

Figure 3 *The rise time of a typical mid-power thermopile (30W) compared with the thin film thermoelectric sensor.*

The response speed of thin film thermoelectric sensors allows users to move beyond just measuring average power, and enables visualization of the temporal pulse shape and peak power of modulated lasers with pulse lengths greater than 10 µs, which can be used to develop better process recipes. These pulses can also be integrated to calculate individual pulse energy for use in active feedback control. It has also found home in process control where the instantaneous response enables end users to measure more frequently, thus improving yield while maintaining high throughput

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