APPLICATION NOTE:
OPTICAL EMISSION SPECTROSCOPY FOR ADDITIVE MANUFACTURING PROCESS CONTROL

Techniques

Optical Emission Spectroscopy

Keywords

- OES Optical Emissions
- Additive Manufacturing
- 3D Printing
- Industrial Process Control

Introduction

3D metal printer produces a steel part

Additive manufacturing, or 3D printing as it is more commonly known, has revolutionized the modern production and design process. Initially developed in 1988 for rapid prototyping, additive manufacturing allows users the ability to produce 3-dimensional physical objects directly from a computer file via layer-by-layer deposition. 3D printing is in stark contrast to traditional subtractive machining, such as CNC "computer numerical control" machining, which relies on the removal of material from the substrate to produce the final product. Additive manufacturing has many advantages over subtractive manufacturing, including reduced waste, increasing internal complexity, and eliminating the need for product-specific tooling. Unfortunately, the process melt involved in direct material deposition can also introduce defects, which have historically limited the usefulness of 3D printers to prototyping applications. These defects commonly result from a wide variety of sources, including melt pool instability, unexpected thermal deformation, environmental anomalies, and energy source fluctuations [1].

As a result, real time monitoring techniques are essential to reduce scrap rates and therefore take full advantage of the potential benefits of additive manufacturing. Monitoring is especially important for metal 3D printing, not only because of the increased materials cost but also the extremely high melt points. Luckily, the high temperatures utilized in metal 3D printing facilitate the integration of passive optical emission spectroscopy (OES). To better understand how OES can be integrated into a metal 3D printer, it is essential to gain a better understanding of the technology. For the sake of brevity, this application note will not go into detail about the fundamentals of OES itself, but If the reader would like more information on the subject, the Avantes application note titled "Plasma Diagnostics and Optical Emission Spectroscopy" is recommended as reference on the topic.

Fundamentals of Metal 3D Printing

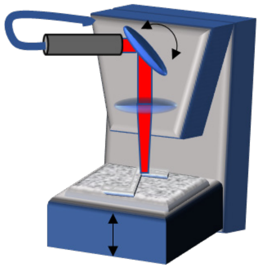

Fig. 1a Schematic of Laser powder bed fusion (LPBF) system

There are two primary methodologies employed for modern direct metal disposition 3D printers: laser powder bed fusion (LPBF) and directed energy deposition (DED) [2] shown in figure 1. Both of these techniques rely on a high-power laser, such as a CO2 or fiber laser, to fuse powdered metal in a preprogrammed pattern, layer by-layer to construct the desired final product. In LPBF, the whole platform is uniformly covered with a thin layer of powder, and the laser-scanned across the bed using galvanometric mirrors and an f-theta focusing lens. After each layer is fused, the platform is then shifted down, and the process is repeated until the construction of the final part is completed. By contrast in DED, the laser is focused on a permanent location with powder jets arranged at the appropriate angle to intersect at the focus of the laser. The material substrate is placed on an X-Y-Z translation stage and then scanned underneath the laser, layer-by-layer, during fabrication. At present, DED processing appears to be the dominant approach for direct metal deposition because of its high throughput, low waste, and larger build volume. However, LPBF is still used for high precision applications when layering heights of less than 250 m are required.

As of today, the predominant choices for metal additive manufacturing materials are Ti-6Al-4V, AlSi10Mg, steels (including stainless), and Inconels (Ni-alloys), for both LPBF and DED printers. However, while both deposition methods are capable of processing all of these materials, unlike LPBF, DED can also utilize wire feed technology. By using a wire feed, DED printer heads can utilize an even more comprehensive range of printer materials at a lower price. For example, additive manufacturing grade 316 stainless steel powder costs, on average, twice as much per pound as 316 stainless steel wire. The only downside to a wire is that the resolution of the system is then necessarily limited by the thickness of the wire, typically on the order of 1 mm in diameter.

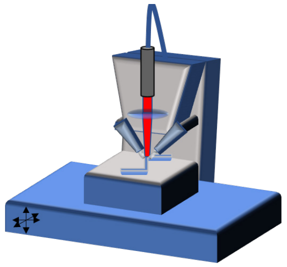

Fig. 1b Schematic of Directed energy deposition (DED) system

OES in Additive Manufacturing:

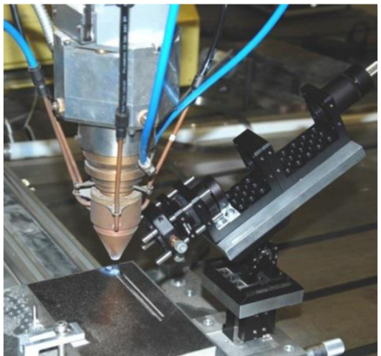

Fig. 2: Picture of fiber-optic cable and collection optics integrated into DED printing head [3].

Based on the geometry of the two primary additive manufacturing processes for metal 3D printing shown above, it is easy to see why OES is such an attractive tool for process monitoring.

Figure 2 below shows an example in which an Avaspec-3648-USB2 was integrated into a DED printing head [3]. In this example, the light was collected by a fiber optic cable oriented at a 60-degree angle relative to the laser's optical axis. In this particular application, the team at the University in Brussels was using OES to monitor the color temperature of the melt pool. While the primary goal of this study was to develop a non-contact control system to prevent excessive heat transfer in the substrate to reduce the material tress, they also demonstrated that defects could be correlated to the presence of oxidation.

Similarly, it has also been shown that monitoring the ratio of atomic emission lines can be directly correlated to the probability of structural defects, resultant from changes in atomic concentrations. For example, a team at Pennsylvania State University showed a direct correlation between atomic titanium and vanadium emissions and defect formation in Ti-6Al-4V [1]. Furthermore, a group out of the University of Michigan used OES to monitor chromium composition in H13 tool steel as a means of real time material characterization, defect detection, process optimization, and process control [4]. As a result, more and more manufacturers are insisting on real time monitoring to detected defects early in the production process.

Spectrometer Requirements

When collecting OES data for additive manufacturing process monitoring, a spectrometer typically requires excellent spectral resolution to differentiate between similar atomic species. As a result, the AvaSpec-ULS4096-EVO from Avantes an ideal choice for this application, shown in figure 3. This spectrometer is capable of providing 0.05 nm resolution within the range from 200 nm to 400 nm using a 3600-groove density grating. Additionally, the AvaSpec-ULS4096-EVO has a CMOS detector array, which is ideal for high light level applications such as this one because of its superior linearity and dynamic range when compared to CCD detectors. When combined with Avantes' proprietary high-speed electronic triggering, data transfer rates, and analog and digital I/O capabilities, the AvaSpec series can provide seamless integration into high-speed inspection systems.

All of the AvaSpec spectrometers are also available as OEM modules so that they can be integrated into turnkey process control systems. These units can communicate via USB, Ethernet, and the native digital & analog input/output capabilities of the Avantes AS7010 electronics board, which provides for a superior interface with other devices. Additionally, the Avantes AvaSpec DLL software development package, with sample programs in Delphi, Visual Basic, C#, C++, LabView, MatLab, and other programming environments, enables users to develop code for their own applications. Furthermore, all Avantes spectrometers are designed to be multiplexed, or concatenated, enabling multichannel operation. This allows each spectrometer in the system to be optimized for spectral resolution over a small range, typically 200 nm – 300 nm, where the OES signal can be split evenly amongst them through the use of a multichannel fiber optic bundle. This can provide for multiple redundant channels or ultra-high resolution configurations covering a broader range. Avantes offers multi-channel configurations as individual modules or integrated into rackmount systems as shown in figure 4.

Fig. 4 Avantes Multichannel Rackmount System

When integrating a spectrometer into a 3D printer head, it is also essential to choose a fiber optic cable that is well suited for the particular environmental conditions. For harsh manufacturing environments, metal-jacketed fiber optic cables provide the highest level of protection from damage, but at the cost of flexibility. Therefore, it is also vital to take into consideration the mechanical constraints of the system, including cable routing and management, when selecting a fiber optic cable. In some cases, high temperature (up to 500 degrees C) fiber assemblies may be necessary if the fiber tip is in close proximity to the melt pool. Avantes offers a variety of fiber cable configuration options to ensure that you can always find the ideal solution for your particular integration needs.

Fig.3 AvaSpec-ULS3648 High-Resolution Spectrometer

For more information about the full range of laboratory and OEM spectrometer options available from Avantes, please feel free to visit the website at www.avantesusa.com or give us a call at +1 (303)-410-8668, where our knowledgeable applications specialists are standing by to help.

References

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