A BOOST FOR ADDITIVE MANUFACTURING

PRIMES ScanFieldMonitor meets nLIGHT AFX-1000

Ring beam lasers, such as the nLight AFX-1000, are getting more and more attention in the industrial environment. The ScanFieldMonitor (SFM) is designed to monitor the state of a laser-scanner system and to maintain the quality of additive manufacturing processes through regular measurement. Here we present a measurement series of an AFX-1000 laser, reveal the origin of oscillations observed in the SFM signals and link the results to PBF-LB/M manufacturing trials.

A major challenge for additive manufacturing processes is their competitiveness with conventional production methods in terms of processing speed and reliability. In recent studies of laser beam powder bed fusion (PBF-LB/M), lasers with ring-shaped and saddle-shaped output beams have shown significantly increased process speeds, enlarged process windows, and a reduction of spatter[1]. These results highlight the importance of characterizing shaped beams, but no uniform standard has yet been established. The combination with laser scanners poses another challenge. Not only the static power density distribution of the laser beam is of interest, but also the characteristics of the beam in motion across a large working area must be considered. To meet the challenge of simultaneously characterizing beam and scanner parameters over the whole scan field, PRIMES has developed the **ScanFieldMonitor (SFM)**.

In this paper, we present a detailed characterization of an **nLIGHT AFX-1000 fiber laser** with a SFM and, as a reference, with a PRIMES **MicroSpotMonitor MSM+**. The setup used in this study, located at the Professorship of Laser-based Additive Manufacturing at the Technical University of Munich (TUM), consists of an AFX-1000 with an **RAYLASE AM-MODULE NEXT GEN** 4-axis scanning system.
To demonstrate the advantages of AFX beams in additive manufacturing, we first measure the energy distribution of the different beam profiles using a SFM, see **Figure 1**. By moving the beam across the scattering structure, the resulting signal is equivalent to the integrated energy distribution of the beam on the powder bed. As a result, the SFM has the unique

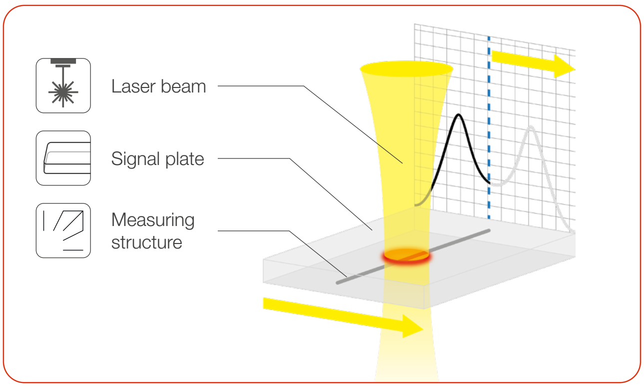

Figure 1: The SFM measurement is based on a line structure engraved in glass. The laser beam is scanned across the line, resulting in scattered light collected by a photo diode.

advantage of being able to measure the intensity distribution as “seen” by the process. Moreover, the SFM can capture scanning laser beams under an angle of incidence of up to 20°, which allows evaluation of variations in the beam intensity distribution across the entire scan field, as well as characterization of any distortions through the scanner system. In order to assess the results of the SFM, the setup is also characterized using the MSM+. This tool is the industry standard in camera-based measuring devices for high-power lasers, delivering full scope beam analysis of stationary beams with the highest accuracy and repeatability.

Both with SFM and MSM+, all 7 beam profiles provided by the AFX laser are measured in the focal plane and under normal incidence, see Figure 2. The profiles differ by the power distribution between the core and the ring. All measurements are repeated at different power levels and – in case of the SFM – at different scan speeds. Both parameters show no significant influence on the measured beam shape. For the results shown in **Figure 2**, a power of 500 W and a scan speed of 1 m/s is used. As the SFM measurements are performed at process speed, a series of 100 vectors is completed within less than 1.1 seconds.

The **nLIGHT AFX-1000** is an advanced fiber laser, enabling highly productive laser powder bed fusion tools, based on nLIGHTs Corona® all-fiber beam-shaping technology. It allows rapid switching of the beam output profile within less than 25 ms between a 14 µm single-mode core, a 40 µm ring, and a variety of shapes in between (“saddle beams”). Specifically, AFX provides 7 beam profiles (“Index” settings) with different power distributions between the central core and the ring. As a result, printing of fine features can be performed with the single-mode beam, while the build-up rate of volumetric sections is increased significantly by applying ring-shaped beams. **For more details visit www.nlight.net/additive**.

The **PRIMES ScanFieldMonitor (SFM)** measures laser beam parameters and scanner parameters at the same time by characterizing the beam in motion instead of in a static configuration. The working principle makes use of scattering structures engraved in a glass plate. When the laser crosses the engraved lines during the scanning movement, scattered light is measured and evaluated. The measured parameters include beam size, vector position, orientation, length, and speed. More complex parameters, such as delay time of the laser, caustic of the beam, and focus shift of the optics, are obtained by advanced evaluation. As a result of the high incidence angle up to 20°, all these param-eters can be measured over the entire build plate. **For more details visit www.primes.de/sfm.**

[1] J. Grünewald et al., Metals 11, 1989 (2021).

[2] Vector is the term used to describe a line conducted by a scanner device.

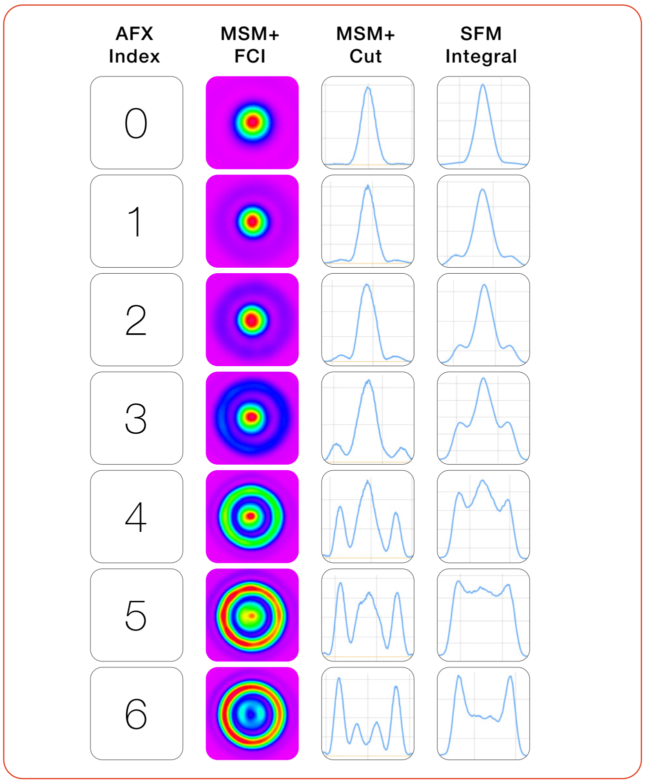

Figure 2: For each of the Indices of the AFX laser a full caustic with the MSM+ is measured. Column 2 shows a false color image (FCI) of the intensity distribution in the focal plane. Column 3 shows a horizontal cut through the FCIs center of gravity. Column 4 shows the signal from the SFM line structure at the focal plane, averaged over multiple vectors.

The MSM+ measurements represent the 2D intensity distribution of each AFX beam profile, ranging from an almost diffraction-limited single-mode spot ("Index 0") to a ring-shaped beam with minimal power in the single-mode region ("Index 6"). With increasing index, a larger fraction of the power is distributed from the central core to the ring of the feeding fiber. For Index 6 the power ratio between core and ring is measured with the MSM+ to be 0.12/0.88. The SFM data shows the scattered energy of the moving beam as an amplitude over time. The recorded intensity signal resulting from the SFM line structure (Figure 1) is transformed from the time domain to position space. Comparing the beam widths resulting from the SFM measurements with those from the MSM+, shows very good agreement, with a deviation of less than 3%.

The energy distribution measured by the SFM shows signal oscillations for all AFX Indices between 1 and 6. This observation is due to the nature of the underlying all-fiber beam-shaping technology of the AFX laser. While single-mode fiber lasers operate on a single transverse mode with a near-Gaussian beam profile, ring beams consist of multiple transverse modes. While delivering the desired average beam shape, such beams exhibit mode beating on rapid timescales. This mode beating results from phase changes among the transverse modes, which depends on a variety of factors (fiber length, vibrations, etc.). The resultant fast fluctuations are not observed in measurements with relatively slow detectors, like thermopiles and many camera-based sensors like the MSM+, but they are resolved with high-speed sensors such as the SFM. Since the MSM+ acquires camera images with an exposure time of several milliseconds or more, it effectively averages over many mode beating cycles and thereby records well-averaged beam profiles.

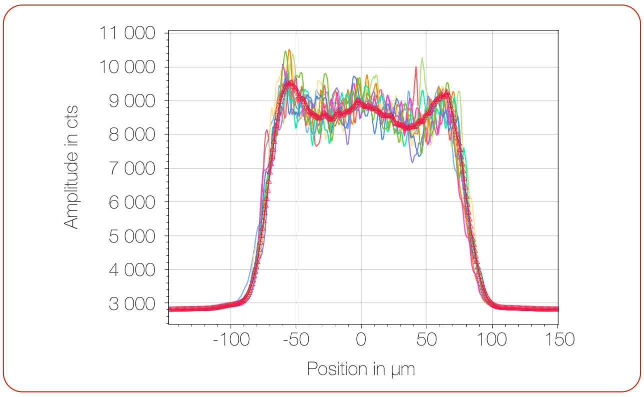

Figure 3: Signal of 10 individual passages of Index 5 over the line structure of the SFM. The oscillation resulting from mode beating is clearly seen. These signals are compared with the average of these 10 vectors (red) in which the oscillations are averaged out, demonstrating their statistical independence.

During an actual PBF-LB/M process performed with an AFX laser, the variations of the energy deposition imposed by the mode beating are effectively averaged out by thermal redistribution within the melt pool, both through heat conduction and melt flow. Therefore, the energy input per cross section by the moving beam perpendicular to its scan direction is well represented by the time-average of the SFM signal. An example is shown in **Figure 3** for Index 5, corresponding to a flat-top intensity distribution on the powder bed. The intensity distribution as measured by the MSM+ shows a power ratio of 0.20/0.80 between core and ring, in agreement with the AFX calibration.

In order to confirm the flattening of the melt pool geometry by AFX ring-shaped beams, PBF-LB/M trials were conducted at TUM with 316L stainless steel at all available AFX Indices. Single trials were conducted with a laser power of 300 W and at a scan speed of 800 mm/s. **Figure 4** shows a vertical cut through two of the printed lines. Compared to Index 0, Index 5 creates a shallow and an almost rectangular melt pool, and thereby effectively reduces balling and keyholing. As a result, the laser power and thus the scanning speed can be increased with Index 5 while maintaining a stable melting process and excellent material quality. The Index 5 beam shows the largest process window with lowest roughness. The productivity of the process is increased from 12 mm³/s (Index 0) to 20 mm³/s (Index 5)[1].

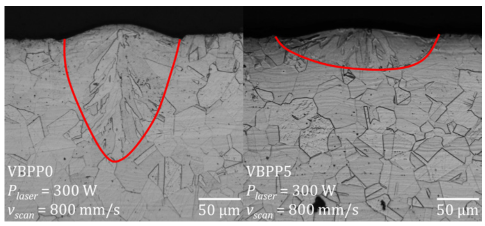

Figure 4: Cross-section of exposed single tracks using AFX Index 0 (left) and Index 5 (right). The red line shows the limit of the solidified melt pool. As expected, a significant reduction in penetration depth is observed when using a ring-shaped beam and no effect of the mode beating is observed.

To summarize, we have shown that the SFM measures the non-Gaussian nLIGHT AFX laser beams precisely. It shows an integrated intensity distribution, which is close to the energy distribution deposited on the powder bed.

We thank the TUM for intensively testing the nLIGHT AFX laser and the PRIMES ScanFieldMonitor.