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High-productivity Laser Powder-Bed Fusion tools enabled by AFX fiber lasers with rapidly tunable beam quality

D.A.V. Kliner[a*], B. O'Dea[a], J. Lugo[a], R.L. Farrow[a], R. Hawke[a], A. Hodges[a], R. Stephens[a], B. Foley[a], K. Almonte[a], B. Kehoe[a], M. Hamilton[a], C. Luetjen[a], J. Small[a], D. Balsley[a], S. Karlsen[a], C. Archer[a], and R. Martinsen[a]

[a]nLIGHT, 5408 NE 88th Street, Building E, Vancouver, WA 98665 USA

Abstract

Laser powder bed fusion (L-PBF) is the leading additive manufacturing technology for producing high-quality, precision parts from a wide range of metals. L-PBF productivity is limited, however, by constraints on build rate and material quality imposed by the near-Gaussian beam shape of single-mode lasers employed in L-PBF tools. We have developed a novel fiber laser (AFX™) that provides a tunable beam shape optimized for L-PBF. The AFX beam is rapidly tunable, directly from the feeding fiber (no free-space optics), from true single-mode (14 µm) to a 40 µm ring, with multiple shapes in between, allowing real-time control of the thermal profile in the workpiece. AFX has been shown to increase the build rate by nearly 8x while maintaining excellent material properties (>99.8% density) and a large process window, enabling a new generation of high-productivity L-PBF tools for series production. We describe AFX technology and application results from several groups.

Keywords: fiber laser; variable beam; beam shape; single mode; ring beam; additive manufacturing; laser powder-bed fusion (L-PBF); series production

1. Introduction

Additive manufacturing (AM) promises previously unimaginable production capabilities in both existing and emerging applications. Laser powder bed fusion (L-PBF) is the leading AM technology for producing high-quality, precision parts from a wide range of metals and alloys. L-PBF productivity is limited, however, by long build times, restricting its use to high-cost parts or prototyping and preventing its deployment for series (high-volume) production. This productivity limitation stems from the use of single-mode (SM) lasers in L-PBF tools.

Typical parts include both fine detail and large-scale features. L-PBF tools employ SM lasers to enable production of fine features, but the resultant small spot size and Gaussian beam shape preclude faster production of larger features. Expanding the beam using a zoom lens does not address this problem because the resultant beam profile is still Gaussian, whose peaky shape causes overheating, resulting in generation of smoke, spatter, and porosity and causing poor material quality. Similarly, expanding the beam by working off-focus retains the nonoptimal Gaussian spatial profile, and this approach also reduces the process window because of the rapid change in beam size with position along the propagation direction when the workpiece is positioned away from the beam waist. Instead, a beam shape that generates a flatter transverse temperature profile in the workpiece is needed. The optimum beam shape depends on multiple parameters, including the thermal properties of the powder and underlying material, the spot size, the scan speed, and the optical power. The ideal L-PBF laser source would thus provide a SM beam for producing fine features and a family of larger beams with optimized shapes for producing larger features. Initial analysis indicated that the desired thermal profiles could be generated by beams with ring shapes and saddle shapes (i.e., ring beams with some intensity in the center). Until recently, no laser source could provide the required performance and versatility.

2. AFX programmable fiber lasers

We have developed a portfolio of fiber lasers whose output beam size and shape are rapidly tunable directly from the feeding fiber. Kliner et al. (2022) present the underlying technology (known as "Corona™"), the optical performance, and application examples from metal cutting, welding, and AM. The key advantages of Corona fiber lasers are:

- All-fiber, eliminating the well-known performance and reliability problems of free-space optics.
- Fast switching of the beam shape (< 25 ms), enabling on-the-fly optimization of each process step.
- High reliability, with accelerated life testing showing no change in performance with >20 million beam changes.
- Large dynamic range (~10x range in beam area from a single laser).
- Wide range of beam specifications available with different fiber designs to address a variety of applications.
- Optimized beam sizes and shapes, including Gaussian (single mode, SM), flat-top, ring, and saddle.
- Power scaling limited only by silica fiber, as with conventional fiber lasers (powers up to 15 kW are currently available).

The multimode family of Corona fiber lasers ("CFX™") is employed for metal cutting and welding. The SM version ("AFX™") is optimized for L-PBF. Specifically, the AFX feeding fiber has a SM core (14 µm mode-field diameter) surrounded by an annular core (40 µm diameter); the output of the laser can be partitioned between the SM and annular cores, enabling the beam profile to be tuned between true SM (Gaussian) and a 40 µm ring, with a variety of shapes in between (Fig. 1). The corresponding beam diameter (second-moment, D4σ) ranges from 15 – 45 µm.

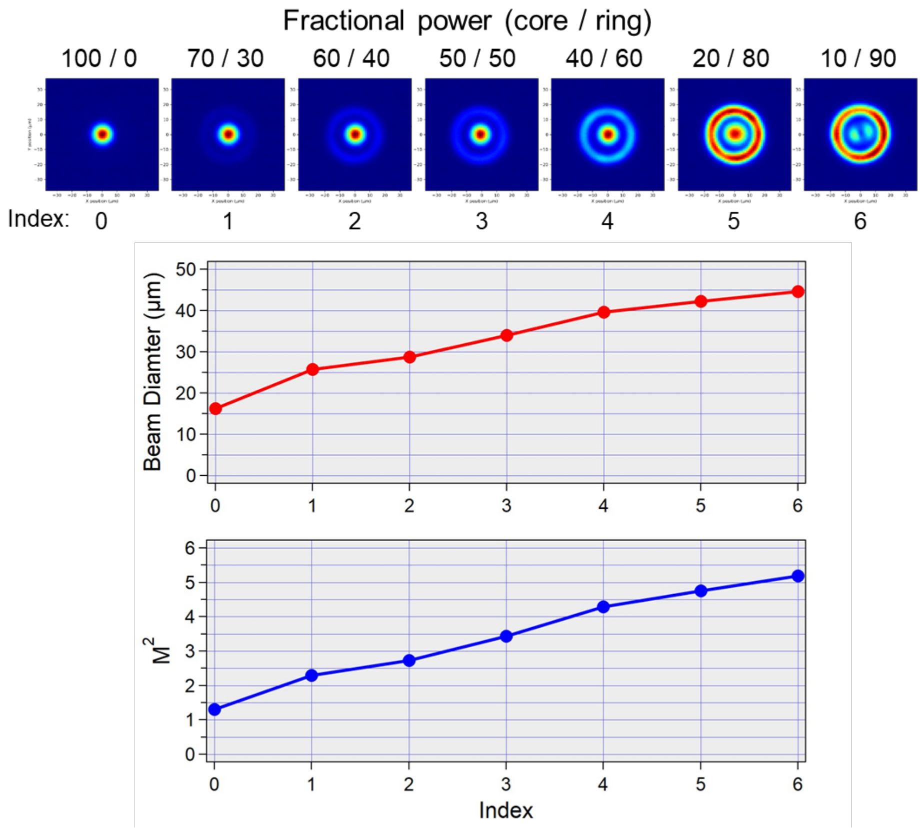

Fig. 1. AFX Index settings. The top images show near-field spatial profiles for the indicated divisions of power between the central core and the annular core. The upper graph shows the calculated D4σ beam diameters, and the lower graph shows the corresponding M^2 values.

We have found that supplying predefined beam shapes ("Index" settings) is preferable to continuous tuning of the beam for process optimization and stability. Industrial lasers are often deployed in electrically noisy environments, in which analog control signals can be unstable on a variety of timescales. By providing defined, digitally selectable ("programmable") beam shapes, the end user is ensured that their laser performance will be stable for years. The number of Index settings and the power distribution among the guiding regions for each setting are software-settable and can be optimized based on the needs of the application or tool.

AFX provides excellent beam quality for all Index settings, with M^2 values between ~1 and 5, resulting in a large depth of focus; for example, with a magnification of 5x (typical for L-PBF tools), the Rayleigh range (Z_R) is 3.4 mm for the SM setting (Index 0), increasing to 8.1 mm for the largest ring beam (Index 6). Furthermore, AFX beams retain their shapes over a significant distance (~½ Z_R) on each side of the beam waist. AFX thus provides a large process window for all Index settings.

AFX is available at power levels up to 1.2 kW. As with conventional SM fiber lasers, the power and feeding fiber length are limited to avoid stimulated Raman scattering. When supplied with a 5 m feeding fiber, the AFX Index 0 – 2 power is limited to 850 W, and the Index 3 power is limited to 1050 W; full power is available in Index 4 – 6. Higher Index 0 – 3 powers are available with shorter feeding fibers.

AFX fiber lasers retain all the standard benefits of other nLIGHT fiber lasers, presented in Kliner et al. (2018), specifically:

- Hardware-based back-reflection protection that enables uninterrupted processing of highly reflective materials and finishes with no requirements to modify processing recipes or tool configurations.
- Industry-leading power tunability (5 – 100%) and stability ($\sigma < 1\%$ over 8 hr). A unique feature of nLIGHT fiber lasers is that the power stability specification pertains over the full power range, i.e., the standard deviation of the power is < 1% of the set point for all power levels between 5% and 100% of full power.
- The fastest modulation rate (100 kHz) and rise and fall times (< 5 µs), enabling sophisticated waveform generation and precise synchronization with external events or among multiple lasers.

Finally, nLIGHT has developed a family of collimators to facilitate AFX tool integration. These collimators feature diffraction-limited optics that maintain beam quality over the full power range for all Index settings. They are designed for high optical power and brightness, with near-zero focus shift and no thermally induced aberrations. They are available with seven focal lengths between 50 and 160 mm. These collimators include optional NA apertures to ensure no beam clipping on scanner input apertures or process optics. The nLIGHT collimators maintain all beam specifications when being added to the laser or changed in the field (i.e., a given collimator is not paired with a given laser).

3. AFX L-PBF results

Several L-PBF tool integrators and research laboratories have demonstrated and quantified the advantages of AFX for L-PBF productivity and part quality. Specifically, AFX significantly increases the L-PBF build rate (by up to 7.8x) while simultaneously increasing the process window and maintaining excellent material quality. This unmatched combination of benefits results from AFX's ability to precisely control heat deposition into the workpiece. In comparison to standard SM beams, AFX's optimized beam profiles dramatically reduce melt-pool instability, reducing generation of soot and spatter that negatively impact material quality and thus production yields. This benefit, in turn, enables the laser power and thus the scan speed and L-PBF build rate to be substantially increased. Recent results include:

- Aconity3D showed that AFX can increase the build rate for a titanium alloy by 7.8x, from 5.4 cm^3/hr for a standard SM fiber laser to 42.1 cm^3/hr for AFX. This increase derived from a 4x increase in the melted volume and a nearly 2x increase in the scan rate while maintaining excellent material quality (>99.8% density).
  (www.youtube.com/watch?v=TsumIEibbk8, see results at time 49:45)
- Grünewald et al. (2021) at the Technical University of Munich (TUM) showed that AFX can simultaneously increase the build rate (by ~2x) and the process window for L-PBF of stainless steel 316L. AFX enabled use of higher laser power and thus faster scan speed with a larger process window (i.e., good part quality over a range of powers). Specifically, attempts to increase the power of the SM Gaussian beam resulted in undesirable balling or keyholing effects, which limit the L-PBF productivity. In contrast, the AFX power for Index settings of 4 – 6 can be increased without such process instabilities, enabling a higher build rate.
- The Powder Bed Metal group at Fraunhofer-IAPT showed a 3x increase in build rate for an aluminum alloy (AlSi10Mg) with outstanding material quality (>99.9% density). Further productivity increases are anticipated with additional optimization.
- Lantzsch et al. (2022) of the Laser Powder Bed Fusion group at Fraunhofer-ILT demonstrated that AFX increases the build rate, process window, and material quality for nickel-base alloy 625.

In addition to these productivity advantages, AFX has opened a new dimension for L-PBF manufacturing by enabling control of the local microstructure and thus material properties. AFX's unique mode profiles provide control of thermal gradients and thus solidification dynamics within the melt pool, which has been found to determine the material microstructure, offering entirely new design possibilities. Because the AFX beam shape can be changed on-the-fly, the microstructure can be engineered locally, imparting new functionality and optimized properties throughout the part:

- Aconity3D compared the AFX ring-shaped mode profiles with defocused Gaussian (SM) beams with similar effective diameters for L-PBF of Inconel 718. They found that the AFX ring beam can increase both the yield strength and the elongation at yield. These key material properties are often anticorrelated, requiring a tradeoff, but AFX has decoupled them. This remarkable capability offers the potential for novel component functionality and performance and, in particular, for variable material properties within a single part.
  (www.youtube.com/watch?v=OjUj23tH4fg)

- The TUM group showed that AFX can control the microstructure and thus material properties of stainless steel 316L. The different AFX beam shapes enable optimization of the geometry and temperature profile of the melt tracks, thereby controlling the grain growth direction and texture, which in turn determine the material properties. Prof. Wudy, who led this research, observed that with such strategic control of grain growth, "the resulting component properties can be fine-tuned – for example, we can make particular parts of a component especially stiff or pliable without any additional post-processing. Properties can also be varied within a single component using sophisticated exposure strategies." (www.raylase.de/en/applications/additive-manufacturing/additive-fertigung-laser-powder-bed-fusion-verfahren.html)

4. Conclusions

AFX fiber lasers represent a breakthrough in fiber laser capabilities, providing a rapidly tunable beam profile directly from the feeding fiber with no free-space optics or other components that degrade performance, stability, or reliability. AFX provides a family of beam shapes optimized for L-PBF, including true SM (14 µm Gaussian), a compact ring (40 µm diameter), and multiple shapes in between, all with excellent beam quality. AFX fiber lasers are available at powers up to 1.2 kW, and the technology is scalable to higher powers and other beam shapes.

AFX fiber lasers have been shown to provide extraordinary gains in L-PBF productivity for several metals and alloys, fundamentally changing the economics of L-PBF manufactured parts. AFX is thus enabling a new generation of high-productivity L-PBF tools, paving the way for L-PBF to become the dominant metal-AM technology for series production. Moreover, AFX's unique ability to control the local microstructure and thus material properties introduces a new frontier to L-PBF. This groundbreaking capability offers the potential to fabricate parts with material characteristics, functionality, and performance unattainable with previous manufacturing technologies.

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