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Enhancing Laser Powder Bed Fusion processes thanks to beam shaping with Multi-Plane Light Conversion

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Abstract

This paper focuses on processing new materials, such as difficult-to-process Ni-based superalloys, using Laser Powder Bed Fusion (L-PBF) in the additive manufacturing industry. L-PBF involves scanning a laser over a bed of powder to melt it where a 3D part needs to be constructed. The two main challenges in L-PBF are improving process yield and processing new materials, which both may be solved with the shaping of the laser beam.
Multi-Plane Light Conversion (MPLC) technology enables industrial robust beam-shaping solutions compatible with L-PBF machines. In this paper we will describe the process improvements using different beam shapes. Especially, these beam-shapers allow for better management of the thermal gradient during the process, resulting in a finer and equiaxed microstructure, reduced residual stress, and decreased risk of solidification cracking. The paper will describe the beam-shapers' performance and process results on different materials, including their mechanical performance analysis.

Keywords: Laser; Additive Manufacturing; powder; Nickel; 3D-Printing; beam shaping; MPLC; cracking; porosity

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1. Introduction: Laser Powder Bed Fusion challenges

Laser Powder Bed Fusion, or LPBF, is an additive manufacturing process. A high-power continuous-wave laser scans a specific path on a bed of metal powder, melting the metal as it passes. This allows parts to be printed in successive layers.

However, it is not without its challenges. One significant issue in LPBF is the occurrence of thermal gradients during the melting and solidification process. These gradients can lead to hot cracking and other defects in the final printed part, jeopardizing its structural integrity and performance.

To address this challenge, researchers have turned to laser beam shaping as a potential solution. By carefully controlling the spatial intensity distribution of the laser beam, it becomes possible to optimize the energy deposition and reduce thermal gradients during the melting phase. This, in turn, helps to suppress the formation of hot cracks, leading to improved mechanical properties and better part quality.

Additionally, the benefits of laser beam shaping extend beyond defect reduction. With more precise control over the energy input, LPBF becomes capable of handling new material classes with low-power lasers machines, such as Ni-based alloys, which were once considered difficult to process due to their unique properties. Enabling the use of these advanced materials unlocks a vast array of possibilities for LPBF applications, from aerospace components to biomedical implants, further solidifying its position as a transformative manufacturing technique at the forefront of modern engineering. Despite the challenges, the integration of laser beam shaping in LPBF paves the way for an exciting future where additive manufacturing continues to reshape industries and revolutionize the way we design and produce complex parts.

2. Solution provides by MPLC technology.

2.1. Multi-Plane Light Conversion

Multi-Plane Light Conversion (MPLC) is a technique that allows performing any unitary spatial transform. Theoretically, it enables the lossless conversion of any set of N orthogonal spatial modes into any other set of N orthogonal modes through a succession of transverse phase profiles separated by free-space propagation serving as a fractional Fourier transform operation. The principle of the MPLC is shown schematically in Figure 1.

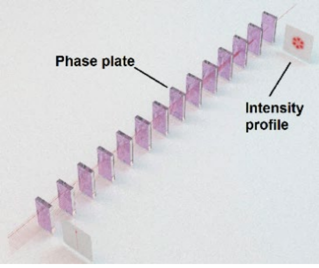

Fig. 1. Principle of MPLC

Historically, MPLC was implemented using a multi-pass cavity, in which the successive phase profiles are all manufactured on a single reflective phase plate (see Figure 2). The cavity is formed by a mirror and the reflective phase plate with the light going back and forward both optics.

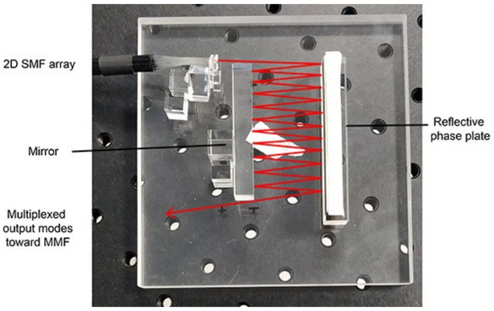

Fig. 2. Picture of a MPLC with fibered inputs. The beam path is shown in red.

MPLC technology enables complex beam shapes with a high control over amplitude and phase. The free-space reflective design allows for high beam shaping quality whilst conserving the property of the laser, such as the depth of field, which is not usually achievable through other beam shaping methods. Moreover, MPLC technology may be adapted to a wide range of wavelengths from visible to IR. Therefore, MPLC technology is well adapted to laser processing.

2.2. System integration

This implementation which has been developed for telecommunication is well suited for macro-processing applications with high-power CW lasers as well with some adaptation. Indeed, instead of having all phase plates one next to the other on one single mirror, the phase plates are each on one mirror, enabling a better management of heat. Even if, each mirror is having a high reflectivity with a global transmission superior to 99%, this configuration enables an extremely robust beam-shaping even at high power, as it has been demonstrated up to 24kW with a very low thermal focus shift (inferior to 1mm at 12kW) for welding applications.

For printing Inconel 939 with the L-PBF method a specific beam-shaping module has been developed and integrated into an EOS M280 machine with a 200W laser and a galvo scanner in the workshops of PresX. (See figure 3 below). This specific machine didn't allow sufficient quality printing of Inconel without beam-shaping.

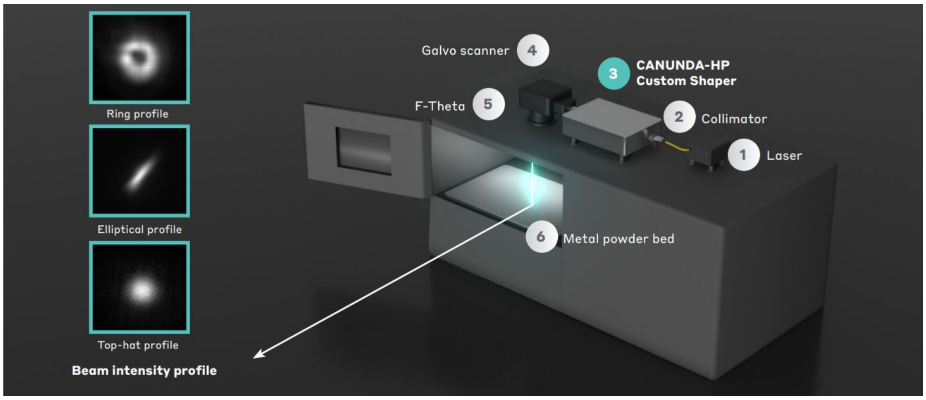

Fig. 3. System integration for LPBF

2.3. Preliminary tests

To print the Inconel 939, three shapes were tested: ellipse, ring, round top-hat. The beams dimensions are 70 µm x 280 µm @1/e^2, 1 to 4 ratio for the Elliptical shape, 150 µm average diameter, 70 µm FWHM for the ring shape and 90 µm diameter @1/e^2 for the round top-hat shape. The elliptical shape has been obtained but the process tests haven't been not performed.

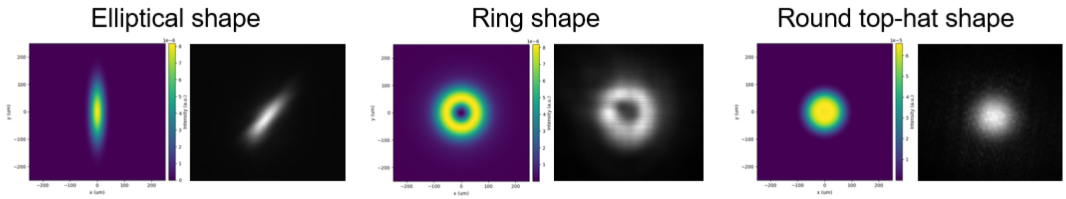

Fig. 4. Intensity profiles in the processing plane

In the quest to print Inconel 939 with the EOS M280, the primary goal lies in discovering the optimal process window for each shape. This window allows for the creation of high-quality printed parts, specifically seven circular rods in Inconel 939 in the whole field of view of the focusing lens, while meeting essential characteristics. The process parameters play a vital role in achieving this objective.

Throughout these tests, we chose a hatch distance of 0.1 mm and a layer thickness of 0.04 mm. The scanning speed will be varied between 550 and 925 mm/s, to determine the process window. To assess the quality of the printed parts, two key aspects are examined: achieving a relative density greater than 99.5% and ensuring that there are no cracks within the components.

2.4. Preliminary tests

2.4.1. Ring shape

The use of the ring-shaped beam allowed the printing of Inconel 939 using this machine. However, the process window is limited. A significant problem encountered is the presence of cracks in most of the samples printed, except for sample #1 produced at a low speed of 550 mm/s. The scanning speed has a significant impact on the structural integrity of printed parts as expected. Additionally, a trend of relative density degradation as scan speed increases was demonstrated.

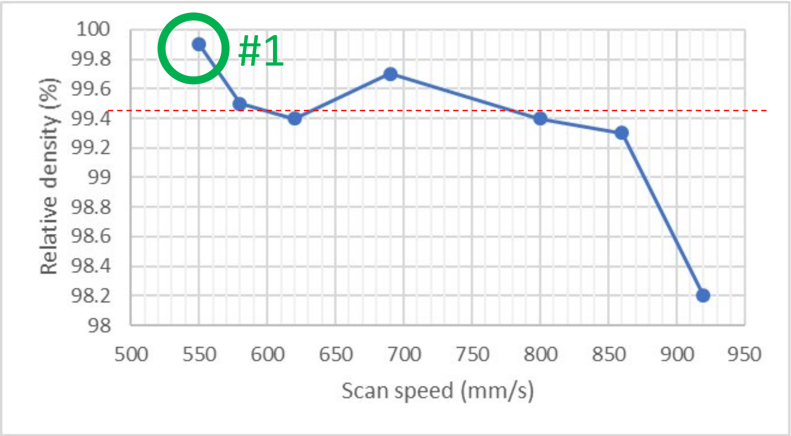

Fig. 5. Relative density of the Inc939 printed piece using ring shape vs scan speed.

For example, on the sample 5 (Figure 6) (800mm/s) we can observe some cracks, circular porosity, and lack of fusion.

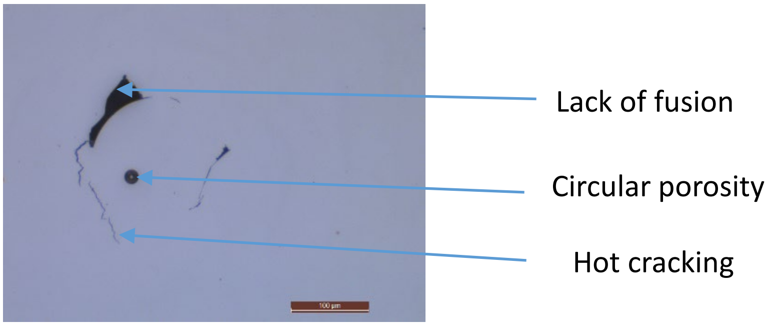

Fig. 6. Inc939 printed at 800mm/s piece using ring shape under the microscope (x200)

2.4.2. Round top-hat shape

The use of the ring-shaped beam allowed the manufacture of Inconel 939 with a large process window. There are no cracks detected on any sample and the relative density is greater than 99.5% on all samples. However, some porosity can appear sometimes.

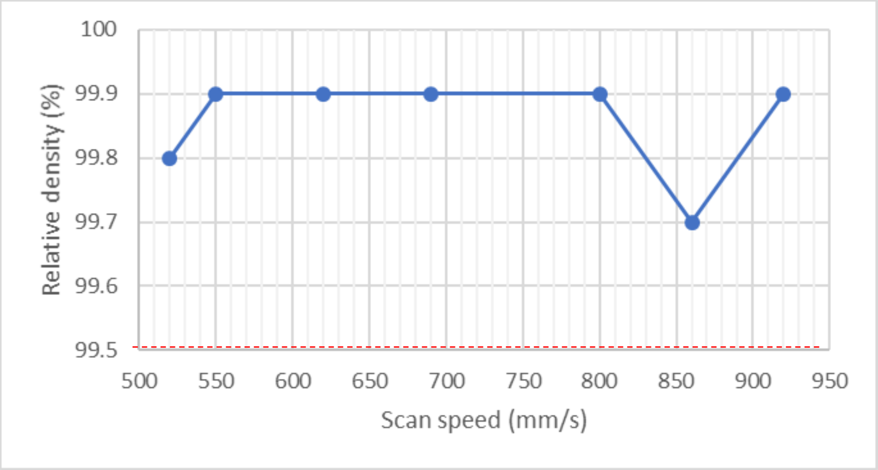

Fig. 7. Relative density of the Inc939 printed piece using round top-hat shape vs scan speed.

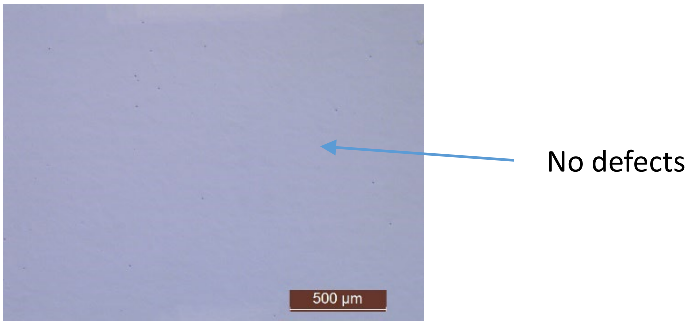

Fig. 8. Inc939 printed at 800mm/s piece using round top-hat shape under the microscope (x200)

2.5. Further investigation on best configurations

To uncover the best configurations for Inconel 939 manufacturing and ensure homogeneity over the entire field of view during printing, extensive investigations have been conducted. Several different tests were carried out to assess the quality of the printed parts and their performance characteristics.

Firstly, the examination involved evaluating cracks and porosity over the full field of view. Five samples were printed in various areas of the printing plate to gauge the consistency and identify potential areas of concern. This provided valuable insights into the distribution of defects and helped in optimizing the printing process to minimize their occurrence.

Micrographic evaluation was another critical aspect of the investigation, focusing on the dimensions of the microstructure within the printed parts. This analysis shed light on the grain structure and overall material integrity, enabling adjustments to be made in the manufacturing process for improved homogeneity and performance.

In addition to micrographic evaluation, mechanical assessments were conducted to determine the mechanical properties of the printed parts. The hardness test provided valuable data on the material's hardness, which is crucial for applications requiring strength and resistance to wear. Furthermore, tensile tests were performed to assess the parts' ability to withstand forces and determine their tensile strength, an important factor in understanding their structural reliability.

According to table 1 just below, the bests results are obtained with the top-hat beam shape.

Table 1. Summary table of test results

Criteria	**Without beam shaping**	**Ring beam shape**	**Top-hat beam shape**
Cracks	**Craks present**	**Crack-free**	**Crack-free**
Porosity	**Porosity present**	**No porosity**	**No porosity**
Microstructure	NA	Thicker microstructure	**Finer microstructure**
Hardness test	NA	Lower properties compared to standard In 939 parts	**Closer properties compared to standard In 939 parts**
Tensile test	NA	Lower properties compared to standard In 939 parts	**Closer properties compared to standard In 939 parts**

3. Conclusion

In conclusion, the collaborative efforts of Cailabs and PresX have yielded remarkable progress in the realm of additive manufacturing, particularly with their EOS M280 machine. Notably, the list of printable materials has been extended to include Inconel 939, showcasing the machine's versatility and ability to handle advanced metal alloys. The successful printing of Inconel 939 also stands out due to the absence of porosity and hot-cracking, ensuring the production of high-quality components with excellent structural integrity. Additionally, the wide process window ranging from 550 to 920 mm/sec provides greater flexibility in fine-tuning the printing parameters, allowing for improved optimization and efficiency.

As part of their dedication to advancing the field, Cailabs and PresX plan to conduct a comprehensive comparison with other beam-shaping technologies.

Other developments are underway, with tests at the Fraunhofer ILT on an Aconity machine equipped with more laser power. Moreover, the development of a new system incorporating a switch between a Ring and a Gaussian beam-shaping technology is a testament to their commitment to continuous innovation. This system aims to enhance process speeds.

Overall, the collaborative efforts and ongoing research initiatives reflect the industry's commitment to pushing boundaries and unleashing the full potential of additive manufacturing. These advancements are poised to revolutionize various industries and pave the way for exciting applications soon.

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