Effect of ring-shaped beam profiles in LPBF of Nickel alloy 718 on the surface roughness

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Abstract. Laser Powder Bed Fusion (LPBF) is an Additive Manufacturing (AM) process which uses a laser, traditionally having a Gaussian distribution, to selectively melts the metallic powders thus allowing the printing of customized parts having complex geometries. Despite the numerous advantages offered by the LPBF, efficiency and productivity of the process represent crucial challenges which limit its large-scale production. In this regard, the use of innovative beam shapes, such as the ring one, is starting to be deeply investigated to potentially revolutionize metal AM by improving quality, efficiency and sustainability of the processes. Nevertheless, very few studies exist in the literature investigating the effect of the use of laser having ring-beam shaped profile on both quality and efficiency of the LPBF process. This work aims to fill this gap of knowledge, thus exploring and discussing the effect of the ring contribution in the LPBF process on both surface roughness and productivity of Nickel alloy 718 parts.

Introduction

Additive Manufacturing (AM) has revolutionized the way of creating objects. In fact, unlike traditional subtractive manufacturing methods, where the material is removed from a solid block, AM processes enables the creation of complex geometries layer-by-layer, by adding material, resulting in creation of custom parts having optimized design potentially impossible to be realized using conventional manufacturing methods [1], [2], [3]. Moreover, AM seems to play a key role in reaching the sustainable development goals [4], [5].

Laser Powder Bed Fusion (LPBF) is an AM process which uses a laser to melt the metallic powders to obtain the desired object. In the LPBF, the process starts with the spreading of the metal powder over a build platform. Then, a laser beam scans across the powder bed and selectively melts the powders. Once each layer is completed, the platform lowers slighglty thus allowing the spreading of a new powders layer. This continuous process ends when the part is completely built. LPBF is finding increasing interest in many industrial fields, such as aerospace, automotive, medical implants, etc., because of ist great offered benefits, such as short time to market, reduced material waste, possibility to obtain complex geometries [6].

Nevertheless, part size, speed, and cost are among the main challenges faced by the LPBF, thus limitating its potential use for mass production.

One of the major drawbacks to LPBF is its slow build speed on the order of 5-10 cubic centimeters per hour print speed [7]. Traditionally, LPBF systems use laser having a Gaussian distribution as a heat source. The traditional Gaussian distribution has a laser beam profile made of a high concentration of energy at the center of the beam with a drop off in energy towards the edges. For instance, some researchers investigated the influence oft he top-hat beam on the LPBF process [8]. A top-hat beam is a light beam having an intensity profile which is flat over most of the covered area, in constrast to traditional Gaussian beams, where the intensity smoothly decays from its maximum on the beam axis to zero [9].

Recently, few researchers started to investigate the use of laser having non-traditional Gaussian distribution with the purpose of overcoming the drawbacks related to the productivity of the LPBF process, without sacrificing the quality of the parts needed to meet the industrial quality requirements.

Among the different currently existing beam profiles, the use of a ring laser beam in LPBF of metal alloys still is now at its infancy because it is a novel technology and very few studies exist on its implications from both mechanical and sustainable perspectives [7], [10].

This work aims to fill this gap of knowledge. It represents a preliminary investigation of the effects of a non-traditional Gaussian beam profile of the laser in the LPBF process on the surface roughness of the parts, pushing the productivity properly selecting the processing conditions. In particular, the effects on the roughness of two modalities, characterized by a Ring contribution in the beam, 50% and 90%, added to the Gaussian one, in comparison of the traditional laser beam, made of 100% Gaussian contribution in the beam profile, are analyzed and discussed.

Materials and Methods

In this work, virgin powders of Nickel alloy 718 were used to print cubic samples into the same job. Table 1 contains their chemical composition. Open Additive PANDA is the machine used to perform the LPBF process in a build volume of 152*152*240 mm^3.

A multi-mode laser nLight AFX-1000 has been used to melt the metal powders layer by layer in the LPBF machine. In particular, the AFX-1000 is a high-power fiber laser which enables switching between a single-mode beam and other beam profiles without the use of space optics. It has a single-mode core surrounded by an annular core. Thus, the output of the laser can be partitioned between the single mode and annular cores.

Seven modalities can be selected going from mode 0, where 100/0 is the fractional power core/ring, to the mode 6, where fractional power core/ring is of 10/90 [11].

Table 1 – Chemical composition of the Nickel alloy 718 virgin powders used in this work

Elements	Al	Cr	Co	Fe	Mn	Mo	Ni	No
Amount %	0.5	18	1	17	0.3	3	55	5.2

In this work, three different modes of the AFX-1000 were selected to investigate their effect on the surface roughness. The three modalities selected are the following:

- mode 0, corresponding to the full Gaussian beam shape, with a 100/0 fractional power core/ring;
- mode 3, corresponding to the half Ring half Gaussian beam shape, with a 50/50 fractional power core/ring;
- mode 6, corresponding to the full Ring beam shape, with a 10/90 fractional power core/ring;

Fig. 1 depicts the three investigated beam shapes.

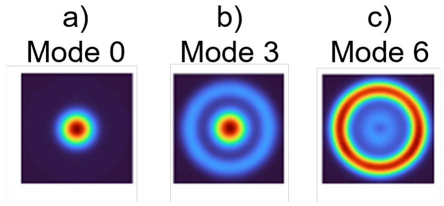

Figure 1 – Beam shape of a) full Gaussian (100% G, mode 0), b) half Ring half Gaussian (50%G – 50%R, mode 3), c) full Ring (10%G – 90%R, mode 6)

The bidirectional line strategy was used to print 10x10x10 mm^3 cubes. Three cubes for each investigated laser mode were printed to evaluate the repeatability of the results, for a total of nine cubes.

For the full Gaussian (mode 0), process conditions recommended by the OEM (Original Equipment Manufacturer) were used to obtain full dense parts. In this regard, a laser power of 285 W and a hatch spacing of 110 μm were selected for mode 0. Higher laser power was selected for mode 3 and mode 6. In particular, a laser power of 412 W and a hatch spacing of 160 μm were selected for both modalities, while keeping constant all the conditions contained in Table 2. This choice was made to push the productivity of the laser, thus taking advantage of the Ring laser beam potentialities. Volumetric Energy Density (VED) was fixed for all the conditions according to the OEM recommendations for the traditional Gaussian laser beam. This choice derives from the purpose of investigating the effect of the laser beam on both productivity and surface roughness while keeping constant the VED, which is one of the major parameters that captures the relationship between energy input and measured mechanical properties and microstructures of the alloys [12]. VED is typically expressed as follows (Eq. 1):

$$VED = \frac{P}{vht} \tag{1}$$

where P is the laser power, v is the scanning speed, h is the hatch spacing, and t is the layer thickness. For all the samples, VED, v and t were fixed for all the samples as contained in Table 2. Moreover, in the choice of laser power and hatch spacing, their ratio was also kept costant, as visible in Table 2.

Table 2 – Process parameters fixed for all the LPBF samples printed in this work

$\boldsymbol{VED\ (J/mm^3)}$	$\boldsymbol{v\ (mm/s)}$	$\boldsymbol{t}$ ($\mu\boldsymbol{m}$)	$\boldsymbol{\frac{P}{h}\ (W/\mu m)}$
67	960	40	2.6

The effect of the beam shape on the surface roughness of the LPBF parts was investigated by using a confocal microscope leica DCM3D according to the EN ISO 4287 standard. Ra and Rz are the roughness parameters used as indicators of the surface quality of the samples.

Results and Discussion

As mentioned in the previous section, in this work nine cubic samples were printed into the same job under three different processing conditions. In particular, some of them were fixed, while others, which are the beam modality, laser power and hath spacing were varied, while keeping constant the ratio between laser power and hatch spacing (Table 2).

These choices were made by considering the OEM recommendations for the full Gaussian mode to obtain full dense parts. In this regard, the first result of this work is an appreciable output in terms of density of the cubic samples: in fact, for all of them, a density around 99% was obtained, thus confirming the printability of the processing conditions selected in this work.

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Table 3 and Table 4 contain the results obtained in terms of roughness of the parts. In particular, three values of Ra and Rz, as a result of three profiles taken on the top of the printed samples, are contained in Table 3 for each of the three samples printed by using the three different modalities. Table 4 contains the average and standard deviation of these measurements. Fig. 2 and Fig. 3 depict the results obtained for Ra and Rz roughness parameters, respectively.

Table 3 – Ra and Rz roughness parameters for all the LPBF printed samples

Mode	Beam	Sample	Ra (µm)	Rz (µm)
0	100% G	1	8.87	43.34
0	100% G	2	12.88	82.81
0	100% G	3	8.28	40.39
3	50%G – 50%R	1	19.04	118.13
3	50%G – 50%R	2	31.97	136.88
3	50%G – 50%R	3	27.01	162.33
6	10%G – 90%R	1	27.97	159.49
6	10%G – 90%R	2	34.98	177.81
6	10%G – 90%R	3	46.46	186.27

Table 4 – Average and standard deviation of the Ra and Rz roughness parameters investigated for all the LPBF printed samples

Mode	Beam	Roughness parameter	Average	Dev std
0	100% G	Ra	10.01	2.50
0	100% G	Rz	55.51	23.68
3	50%G – 50%R	Ra	26.00	6.52
3	50%G – 50%R	Rz	139.11	22.18
6	10%G – 90%R	Ra	36.47	9.33
6	10%G – 90%R	Rz	174.52	13.69

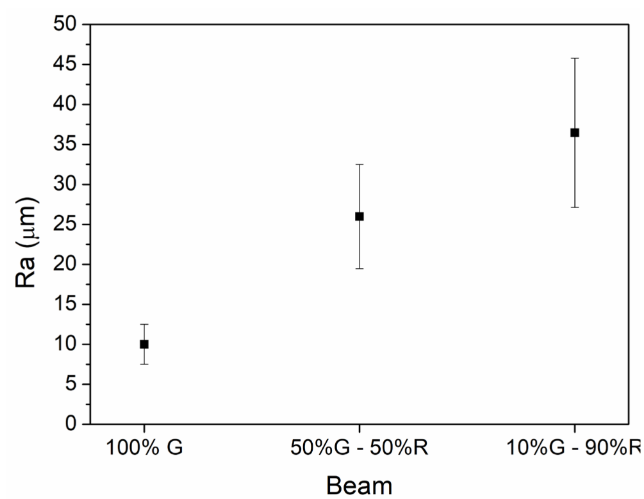

Figure 2 – Ra roughness results for all the laser beam investigated in this work

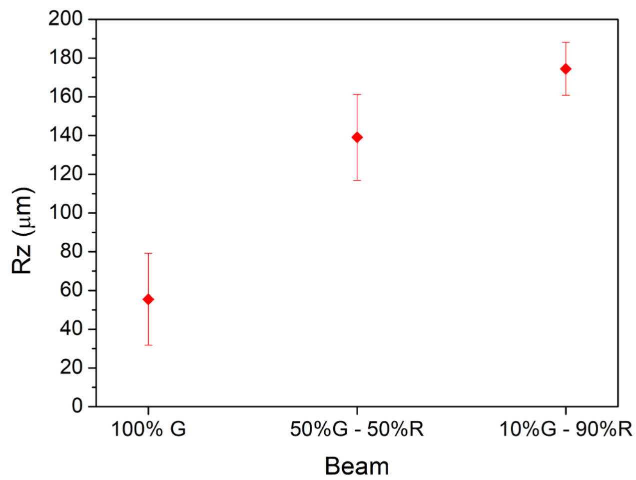

Figure 3 – Rz roughness results for all the laser beam investigated in this work

Both Fig. 2 and Fig. 3 show an increase of the roughness with the increase of the ring contribution while the Gaussian contribution decreases. In particular, Ra on the printed samples can be twice the reference case – the full Gaussian one (mode 0) – selecting the half ring half Gaussian modality (mode 3) reducing up to 50% the Gaussian contribution and can be even more than three times the reference case selecting the full Ring modality (mode 6). The same trend is followed by the Rz parameter as well.

These results are justified by the presence of waves on the surface of LPBF printed samples, which become more pronounced by going from mode 0 to mode 6, as observable by the microscope observation in Fig. 4. Spot size with the ring beam is wider, while the amplitude intensity is lower than the full Gaussian. This strongly affects the surface roughness, as a result of different temperature and beam profiles.

One of the potentialities of the ring beam shape is the increase of productivity. In fact, the beam profile allows laser power and hatch spacing, thus reducing time to produce the same full dense part. In the investigation of this work, the choice of the processing conditions above mentioned for mode 3 and mode 6 allowed to increase the productivity, expressed as the printed volume in the unit time, up to 28 %, as visible in Fig. 5.

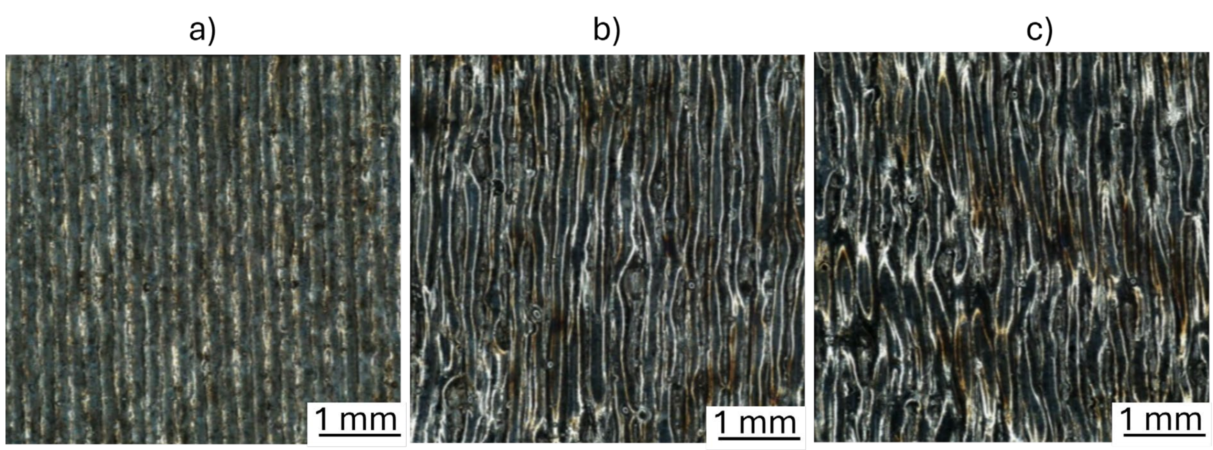

Figure 4 – Surface of the sample 1 of each laser beam investigated in this work: a) full Gaussian, b) half Ring half Gaussian, c) full Ring

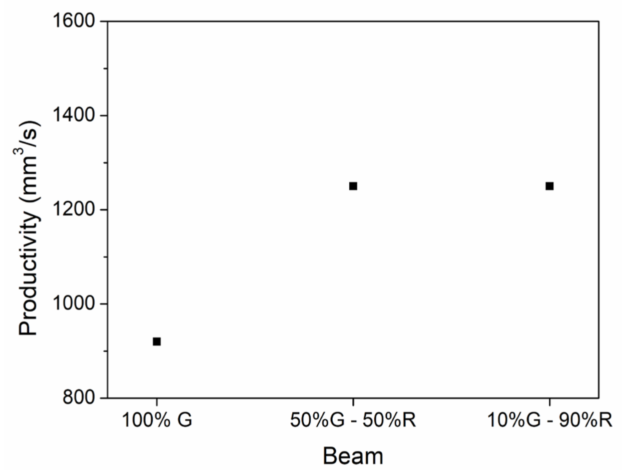

Figure 5 – Productivity for all the laser beam investigated in this work.

Conclusion

This work investigates the effect of the ring beam shape profile on the surface roughness of Nickel alloy 718. In this regard, some cubic samples were printed into the same job by using the same LPBF machine and the same innovative laser system by selecting three different modalities: the traditional full Gaussian, the half ring and half Gaussian modality and the full ring modality. The main conclusion which can be enucleated are the following:

- A non-traditional beam shape, like the ring one, enables to reach full dense parts printed by LPBF as the traditional Gaussian one does.
- The beam shape profile in the LPBF strongly affects the surface roughness of the printed parts.
- Both Ra and Rz roughness parameters can becomes three times higher by selecting a full ring mode rather than the full Gaussian one.
- A ring laser beam enables to select higher hatch spacing and laser power, resulting in an increase in productivity up to 28%.

Thus, this work shows the potentialities of using other beam shapes, like the ring one, in the LPBF to increase the productivity of the process by adopting a VED recommended by the OEM for the traditional gaussian. Further investigation will include a wider process window to highlight eventual limits due to the potential defects that have occurred. Also, additional research is needed to investigate the effects of the ring beam shape profile on the melt pool size, mechanical properties, microstructure of Nickel alloy 718 and other typically printed metal alloys such as aluminum and titanium alloys. Also, the increase of productivity requires to be more in depth analyzed to investigate how effectively can also positively affect the life cycle impact assessment of the LPBF process, which is known to be very energy intensive.

References

[1] E. Hosseini and V. A. Popovich, "A review of mechanical properties of additively manufactured Inconel 718," *Addit Manuf*, vol. 30, no. February, p. 100877, 2019. https://doi.org/10.1016/j.addma.2019.100877

[2] W. E. Frazier, "Metal additive manufacturing: A review," *J Mater Eng Perform*, vol. 23,no. 6, pp. 1917–1928, 2014. https://doi.org/10.1007/s11665-014-0958-z

[3] K. Kellens, R. Mertens, D. Paraskevas, W. Dewulf, and J. R. Duflou, "Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing?," *Procedia CIRP*, vol. 61, no. Section 3, pp. 582–587, 2017. https://doi.org/10.1016/j.procir.2016.11.153

Materials Research Proceedings 54 (2025) 238-244 https://doi.org/10.21741/9781644903599-26

[4] G. Technologies and A. Manufacturing, “Metal Additive Manufacturing Gas Solutions for Sustainable”.

[5] A. W. Boeing and C. Marcham, “Environmental Advantages in Additive Manufacturing,” *Professional Safety/ASSP*, vol. 65, no. 1, pp. 34–38, 2020, [Online]. Available: https://commons.erau.edu/publication

[6] T. Kurzynowski, E. Chlebus, B. Kuźnicka, and J. Reiner, “Parameters in selective laser melting for processing metallic powders,” *High Power Laser Materials Processing: Lasers, Beam Delivery, Diagnostics, and Applications*, vol. 8239, no. February, p. 823914, 2012. https://doi.org/10.1117/12.907292

[7] E. Cozzolino, A. Tiley, A. J. Ramirez, A. Astarita, and H. Edward D., “Energy Efficiency influence of Gaussian and Ring- shaped beam profiles for LPBF,” pp. 1–25, 2023, [Online]. Available: https://orcid.org/0009-0007-6609-0722

[8] C. Tenbrock *et al.*, “Influence of keyhole and conduction mode melting for top-hat shaped beam profiles in laser powder bed fusion,” *J Mater Process Technol*, vol. 278, p. 116514, Apr. 2020. https://doi.org/10.1016/J.JMATPROTEC.2019.116514

[9] A. F. H. Kaplan, “Modelling the Primary Impact of an Yb:Fibre Laser Beam Profile on the Keyhole Front,” *Phys Procedia*, vol. 12, no. PART 1, pp. 627–637, Jan. 2011. https://doi.org/10.1016/J.PHPRO.2011.03.079

[10] J. Grünewald, F. Gehringer, M. Schmöller, and K. Wudy, “Influence of Ring-Shaped Beam Profiles on Process Stability and Productivity in Laser-Based Powder Bed Fusion of AISI 316L,” pp. 1–18, 2021.

[11] “High-productivity laser powder-bed fusion tools enabled by AFX fiber lasers with rapidly tunable beam quality.”

[12] B. Stegman *et al.*, “Volumetric energy density impact on mechanical properties of additively manufactured 718 Ni alloy,” *Materials Science and Engineering: A*, vol. 854, p. 143699, Sep. 2022. https://doi.org/10.1016/J.MSEA.2022.143699