Improvement of Part Accuracy by Combination of Pulsed Wave (PW) and Continuous Wave (CW) Laser Powder Bed Fusion

Thomas Laag¹, Till Martin Winkel¹, Lucas Jauer², Daniel Heussen¹, and Constantin Leon Haefner¹

¹Fraunhofer ILT – Institute for Laser Technology, Aachen, Germany
²Digital Additive Production DAP, RWTH Aachen University, Aachen, Germany

Received April 5, 2022; accepted April 13, 2022; published online June 28, 2022

Abstract: In this paper, a processing strategy is investigated to increase the geometric accuracy of parts fabricated by laser powder bed fusion (LPBF). Pulsed wave emission (pw) is used for contour exposure in combination with a continuous wave (cw) emission for bulk volume exposure. With the goal of discrete solidification of adjacent melt pools, process parameters of laser power PL, scanning speed vs, and relative pulse overlap Δxo are developed for contour exposure. Samples with variable contour angles are fabricated to investigate the effect of the pw contour exposure on excessive melting in critical areas of the part prone to overheating. Geometric accuracy and surface roughness are evaluated using SEM images of surface topography and optical surface roughness measurements, respectively. It is observed that excessive melting can be suppressed by using pw contour exposure and usage of modified process parameters. Due to the discretized energy input in pw emission mode, smaller melt pools with lower melt pool fluctuation and powder erosion are produced. The maximum applicable scanning speed is limited by the solidification time of the melt pool and is significantly lower compared to conventional cw contour exposure parameters. Therefore, a combination of cw volume exposure with high process productivity and pw contour exposure for high geometric accuracy is beneficial to limit productivity losses and increase accuracy in part building.

Keywords: Additive Manufacturing, Pulsed wave LPBF, Continuous wave LPBF, Geometric accuracy, Discrete solidification, Adaptive processing, Surface texture
1. Introduction

Laser Powder Bed Fusion (LPBF) is a powder-bed based additive manufacturing (AM) technology of increasing industrial relevance. Due to layerwise local melting of a part geometry defined by a CAD model using a laser beam, complex part geometries (e.g. thin wall structures, freeform geometries) can be fabricated. As a result of the process characteristics, near-net-shapped parts are produced, which require form corrective post processing steps to decrease geometric deviations if high part accuracy is needed [1–3]. In addition to the surface topology and surface roughness, the geometric accuracy of the built component contour in relation to the CAD model determines the post-processing effort required to correct the shape. However, shape-correcting post processing by tool-assisted subtractive manufacturing is challenging or even impossible for these complex geometries. Therefore, improving the quality of the as-built part is of great importance, especially for high-accuracy applications.

Research has identified two main categories for geometrical errors, related to the data preparation (e.g. resolution of the .stl-file) and the process parameters itself [4]. Since the dimensions of melt pools generated by contour exposure are defining the final shape of the part, controlling the energy input to the edge regions is advantageous to control and limit the dimensions of the melt pool. In general, with increasing energy input, dimensions of the melt pool increase [5–8]. Melt pools within the contour of the built part tend to melt excessively, increasing the size of the melt pool, because the surrounding powder bed limits heat dissipation from the fusion zone [9]. Increasing melt pool volume leads to increased melt pool fluctuations and thus increased geometric deviations from the CAD-defined contour, which is particularly observed in the production of thin-walled structures [10].

In contrast to a continuous wave (cw) laser emission, a pulsed wave (pw) emission enables enhanced control of the dimensions of the melt pool. In the pw emission mode, the energy deposition is discretized by usage of laser pulses generated by gain-switching (µs-pulses), Q-switching (ns-pulses), and mode-locking (fs-pulses) [11–15].

In the pw emission regime, melt pools are created during exposure time defined by the pulse duration parameter [16]. During the laser off-time, the generated melt pool cools down and (partially) solidifies before the next melt pool is generated by the following laser pulse. Due to the discretized energy input and intermittent solidification of the melt pools in comparison to cw emission, smaller melt pool volumes are generated and Marangoni flows are reduced, limiting uncontrolled melt pool movements and therefore geometric deviations [8, 14, 16–18].

Most research uses either cw LPBF or pw LPBF throughout the entire exposure area within the work plane [11, 14–16, 19]. In contrast to this work, this study investigates a complementary use of cw and pw transmission modes under the following constraints:

The cw emission mode is used for exposure of the workpiece volume. As reported in [14] due to the higher energy input for a given laser power and scan speed, cw emission mode achieves higher scan speeds and thus higher process productivity for densely solidifying parts compared to pw exposure.

The pw emission mode is used only for the outer part contour. Process parameters are set to achieve discrete solidification between adjacent melt pools. Discrete solidification is characterized by by the previous melt pool being fully solidified before the subsequent melt pool is generated. In this approach, the dimensions and variations of the melt pools are expected to be minimized. As a result, higher geometric accuracy is expected compared to cw contour exposure.

2. Experimental Methods

2.1 LPBF Machine

Experimental investigations were carried out on a customized Trumpf TruPrint3000 (Trumpf Laser & Systemtechnik GmbH) LPBF machine containing a Ø = 300 mm build plate. The machine is equipped with one single-mode laser (SPI SP 500, SPI Lasers UK Ltd.) that can be operated both in cw and pw emission modes with a maximum nominal laser power $P_l = 500\,\text{W}$, a nominal wavelength $\lambda = 1070\,\text{nm}$ and a spot diameter $d_S = 100\,\mu\text{m}$ in the focal plane.

The pw emission is achieved by a modulation of the laser pump current using a gainswitch. This method of pulse generation is called “pulse-modulated emission”. For the given laser, pulse durations of $t_p \geq 50\,\mu\text{s}$ can be applied. A schematic comparison of cw and pw emission mode is given in Fig. 1a, b. Due to the temporal discretization of energy deposition in the pw emission mode, expressed by the pulse duration $t_p$ and pulse frequency $f_p$, additional processing parameters have to be taken into account to ensure a sufficient bonding within the melt track through the spatial pulse overlap $\Delta x_0$. Moreover, for a given laser power $P_l$ and scanning speed $v_s$, the line energy input in the pw emission mode is reduced compared to the cw emission mode due to intermittent breaks of exposure during the laser off-time (compare the dashed areas in Fig. 1a, b).

2.2 Material

For all experimental investigations, gas atomized powder of the nickel-base alloy Inconel 718 (supplied by Oerlikon Metco) with a nominal powder fraction of –15+45 µm was used. The chemical composition according to the supplier’s data sheet [20] is shown in Table 1. The images
of the powder particles in Fig. 2a, taken by scanning electron microscopy (SEM, LEO 1455 Ep, Zeiss SMT AG), show mostly spherical particles with some satellites, while metallographic cross sections reveal minor contents of porosity. The particle size distribution, measured by Camsizer X2 (Retsch Technology GmbH) powder analyzer, shows a significant amount of fine particle fraction (diameter <10 µm).

2.3 Process Development

For this contribution, process parameters for a pw contour exposure were investigated, while the hatching region of the specimen was manufactured by conventional cw exposure. Additionally to conventional process parameters, the pw emission mode is characterized by parameters defining temporal laser emission behaviour, e.g. pulse duration $t_p$, pulse frequency $f_p$, and geometric parameters such as (relative) spatial pulse overlap $\Delta x_0$.

To investigate the effect of the pw exposure for different contour angles in two different orientations, two different specimen geometries were manufactured within each experiment. The geometry in Fig. 3a was fabricated to vary the contour angle within the exposure plane (xy-plane), while the geometry of Fig. 3b was used to investigate different angles along the build direction (x-z-plane). Afterwards, the identified process parameters were transferred to a franzis turbine as a demonstrator part (Fig. 3c). To evaluate the surface topology (see Fig. 4a and 10), cubic specimens were fabricated and the SEM images of side surfaces were captured.

In total, three experimental set ups were carried out. Within all set ups, only the process parameters for the pw contour exposure were varied, while the parameter set for the cw hatch exposure was kept constant. The cw hatch vectors with a spacing $\Delta y_h = 110 \mu m$ were rotated 66.7° in between consecutive layers. Laser power $P_L$ and scanning speed $v_s$ for hatch and contour exposure were set according to the reference parameter set provided by the machine supplier. For all experiments, a constant layer thick-

| TABLE 1 Chemical composition of powder of alloy Inconel 718, according to the data sheet from powder supplier Oerlikon Metco [20] |
|-----------------|---|---|---|---|---|---|---|---|
| Element         | wt.-% | Ni | Cr | Fe | Nb+Ta | Mo | Ti | Al | Others |
|-----------------|-------|----|----|----|-------|----|----|----|--------|
| Ni              | Bal   | 18 | 18 | 5  | 1     | 0.6| <0.5|     |         |
Honeycomb structure as sealing

Fig. 3: Specimens manufactured for geometric accuracy assessment for different contour angles in xy-plane (a), xz-plane (b), and demonstrator part geometry (c). (Adapted from [21])

Fig. 4: SEM images of build part contour and surface topography of reference specimen manufactured with cw contour exposure. a Contour angle = 15°, b contour angle = 5° + 45°, c surface topography, melt pools of cw contour indicated by dashed lines. a, b 100 x magnification, c 400 x magnification. (z build direction)

TABLE 2

| Parameter study | Parameter | Range          | Increment |
|-----------------|-----------|----------------|-----------|
| P1              | Laser power \( P_L \) | 92–175W | 75W |
|                 | Scanning speed \( v_S \) | 50 mm/s | Const. |
|                 | Contour offset \( \Delta y_c \) | 100 \( \mu m \) | Const. |
|                 | Relative pulse overlap \( \Delta x_o \) | 0.3 | Const. |
|                 | Pulse frequency \( f_p \) | 672 Hz | Const. |
| P2              | Laser power \( P_L \) | 130W | Const. |
|                 | Scanning speed \( v_S \) | 100–175 mm/s | 25 mm/s |
|                 | Contour offset \( \Delta y_c \) | 40 \( \mu m \) | Const. |
|                 | Relative pulse overlap \( \Delta x_o \) | 0.3 | Const. |
|                 | Pulse frequency \( f_p \) | 1270–2051 Hz | Varying |
| P3              | Laser power \( P_L \) | 130W | Const. |
|                 | Scanning speed \( v_S \) | 86/71/56/50 a mm/s | Varying |
|                 | Contour offset \( \Delta y_c \) | 40 \( \mu m \) | Const. |
|                 | Relative pulse overlap \( \Delta x_o \) | 0.4–0.7 | 0.1 |
|                 | Pulse frequency \( f_p \) | 1344 Hz | Const. |

*\( v_S = 50 \text{ mm/s} \) is the lower limit scanning speed defined by the machine settings
ness $D_S = 40 \mu m$ and a constant spot diameter $d_S = 100 \mu m$ was applied. For the pw contour exposure, laser on-time $t_{on} = 125 \mu s$ was set constant for all investigations. Argon was used as a shielding gas, and no preheating of the build plate, made of alloy C45, was applied.

In the first experiment (P1), a suitable process region, indicated by a sufficient metallurgical bonding between the layers was identified by a varying laser power $P_L$. For the pw contour exposure, the laser power $P_L$ defines the nominal peak power within a pulse. In the following experiment (P2), the effect of increasing the scanning speed $v_s$ on the discrete solidification behaviour of the contour melt pools was examined with the aim to identify the maximum scanning speed where discrete solidification is observed. In the final experiment (P3), the spatial relative pulse overlap $\Delta x_o$ was varied and in accordance the scanning speed $v_s$ was adjusted to investigate possible influences of the pulse overlap on the surface topology. The process parameters investigated for each set up are summarized in Table 2. For each experiment, specimens with different contour angles ranging from $5\degree$–$45\degree$, as depicted in Fig. 3, both in the xy-plane and xz-plane, were manufactured. SEM images of the specimens were taken to evaluate the pw contour morphology and resolution of the contour corners. Metallographic cross sections to evaluate the discrete solidification mode of the contour melt pools of selected specimen were ground with silicon carbide grinding paper, polished using diamond suspension of 1 $\mu m$ grain size for four minutes, and etched afterwards for 30 s. A mixture of 75 ml ethanol:25 ml hydrochloric acid:5 ml hydrogen peroxide was used as etchant.

2.4 Demonstrator Part Geometry

The transferability of the results from fundamental process development studies to possible industrial applications has been investigated by manufacturing of an adapted Francis turbine demonstrator as depicted in Fig. 3c. The original .stl-file was downloaded from [21]. After adaption, the demonstrator includes features such as thin wall structured honeycomb sealings and thin walled turbine blades as critical features for the application of pulse-modulated contour exposure. The turbine blades have been fabricated support-free to investigate potential benefits of a pulse-modulated contour exposure on heat induced distortion of thin walled structures. For a comparison between pw and cw contour exposure, the same part geometry has been manufactured using the continuous reference parameter set, No preheating was applied. The geometric accuracy has been measured for both parts using an ATOS GOM (GOM GmbH) 3D-Scanning system.

3. Results and Discussion

3.1 Effect of Laser Power $P_L$

For a qualitative comparison between cw and pw contour properties, the contour properties and surface topography of specimens fabricated with cw reference parameters are illustrated in Fig. 4. Significant areas of melt pool enlargement due to excessive melting and hence pronounced geometric deviations are observed for both orientations (areas marked in red in Fig. 4a, b). The surfaces of specimens fabricated with a cw contour exposure show a layered structure (melt pool boundaries are indicated with dashed lines) in build direction due to the layer wise manufacturing process (Fig. 4c). Only a few powder agglomerates are sintered to the solidified contour melt traces, which exhibit smooth and homogenous melt pool surfaces without signs of a lack of fusion or balling.

The melt pool volume and geometries are directly dependent on the laser energy input into the powder bed [5]. This dependency is also valid for the discrete energy deposition mode as applied in the pw contour exposure and illustrated in Fig. 5. Different from cw LPBF, the dimensions of the melt pool are directly dependent on the pulse energy (the energy transported within one pulse). Hence, as can be observed in Fig. 5a–c, the dimensions of the melt
pool, e.g. melt pool width and depth, increase when increasing the laser power $P_L$. While for $P_L=92\,\text{W}$ (Fig. 5a) lack of fusion is observed between adjacent pulses, a more stable melting is observed for an increased laser power $P_L$ (Fig. 5b, c). Consequently, the corner tip radius is increasing for an increased laser power $P_L$ as well. Caused by a too large contour offset $\Delta y_c = 100\,\mu\text{m}$, which was therefore reduced for the following experiments, pore seams occur in all investigated specimens with pw contour exposure. In contrast to the specimen manufactured with a pw contour exposure, the specimen manufactured with cw reference parameters shows a homogenously molten contour melt track with only minor porosity. Due to the significantly higher energy input compared to the specimens with a pw contour exposure, excessive melting is observed in the tip of the corner, leading to significantly enlarged melt pool dimensions reducing the geometric accuracy as shown in Fig. 4a, b and 5d.

### 3.2 Effect of Scanning Speed $v_s$

For a given spatial pulse overlap, increasing the scanning speed $v_s$ leads to increased pulse frequencies $f_p$ and hence reduced time intervals between consecutive pulses. When this time interval falls below the melt pool solidification time, the previously generated melt pool is not fully solidified before the following melt pool is generated, and, thus, complete discrete solidification of the melt pools is not established. As a result, molten liquids of adjacent melt pools might merge and form a larger melt pool with increased melt pool movements. In consequence, increased geometric deviations might occur. Hence, for the given processing parameters, the knowledge of this transition area is necessary to ensure both a sufficient build part quality and a process productivity.

In Fig. 6, exemplary SEM images of pw contours manufactured with different scanning speeds are shown. The contours of specimens fabricated with a scanning speed of $v_s=100\,\text{mm/s}$ and $v_s=125\,\text{mm/s}$, respectively, show discretely solidifying melt pools, while specimens fabricated with higher scanning speeds reveal (partially) merged melt pools within the contour. Due to the merging of the melt pools, these specimens also show signs of increased height differences within the contour melting track. In general, these height differences might affect the powder deposition and melting of following layers. However, within this study none of the specimens investigated showed characteristics of insufficient melting.

As can be seen from Fig. 7, the corner tip width increases from 127 to $155\,\mu\text{m}$ when the scanning speed is increased from $v_s=100\,\text{mm/s}$ to $v_s=175\,\text{mm/s}$. Since the spot diameter used within this study was set to $d_S=100\,\mu\text{m}$, a larger corner tip indicates a higher degree of excessive melting and therefore a decreased accuracy. Hence, along with an increased scanning speed, the geometric accuracy of the contour in the vicinity of the corner decreases. The contours manufactured with a scanning speed $v_s=100\,\text{mm/s}$ (Fig. 6a) show pronounced and precisely shaped edges, while, with an increasing scanning speed, an increasing agglomeration of the adjacent melt pools is observed (Fig. 6c, d). This indicates a decreasing degree of discretely solidifying melt pools and, hence, an increased merging of adjacent melt pools.

By metallographic etching, the melt pool boundaries within the pw contour can be observed and, hence, the regions of discrete solidification can be identified. It can be seen from Fig. 7, that, for all investigated scanning speeds, a transition from discrete solidification to merging melt pools, indicated by vanished contour melt pool boundaries, is observed in the vicinity of the contour corner. As a consequence of the angled specimen geometry, the reduced solidified material is located below the exposed melt pool. The closer the melt pool is located to the contour corner, heat dissipation out of the fusion zone through the solidified material is increasingly impeded. As a result, solidification time of the melt pools increase so that a discrete solidification is not fulfilled anymore. With an increasing scanning speed, the afore mentioned transition tends to occur in an increasing distance from the contour corner, as indicated with the measurements marked in red in Fig. 7. With an increasing scanning speed, a higher pulse frequency is necessary for a constant pulse overlap (see parameter study P2 in Table 2). Thus, a higher amount of deposited energy per time unit must be dissipated through the solidified material underneath. Therefore, assuming a constant temporal heat dissipation rate of the solidified material, an increased heat accumulation is expected with an increased scanning speed. In consequence, an insufficient heat dissipation occurs in larger areas of the contour and increased corner tip radii are observed.

Similar effects can be observed for the second specimen geometry (see Fig. 3b) as shown in Fig. 8. Homogeneous melt tracks within the last layer are only observed for the scanning speeds of $v_s=100\,\text{mm/s}$ and $v_s=125\,\text{mm/s}$, re-
spectively. Especially for an angle of 45° indications for instable melting due to merging melt pools are observed.

3.3 Effect of Spatial Pulse Overlap $\Delta x_o$

Exemplary SEM images of contour corners are depicted in Fig. 9 for a nominal contour angle of 15°. For all overlaps, discretely solidifying melt pools, indicated by boundaries in between adjacent pulses, are observed. With an increasing pulse overlap, the edge of the contour corner is more pronounced leading to an increased geometric deviation. This observation can be explained by the increased energy input per unit length in the contour as more pulses have to be generated with an increased pulse overlap for a sufficient bonding. Because of the discrete energy deposition in pw LPBF, the line energy input is, under the condition of a constant pulse frequency and pulse duration as applied in this experimental setup, directly connected to the number of pulses generated per unit length. Due to the increased energy input, an increased amount of process induced heat needs to be dissipated through the solidified material underneath. Hence, a melt pool enlargement in the corner edge is increasingly observed with an increased pulse overlap.

Furthermore, an increased amount of sintered powder agglomerates at the side surfaces of the edges is observed, when increasing the pulse overlap from 0.4 to 0.7. This observation is confirmed when analyzing the surfaces via SEM and assessment of the arithmetic surface roughness $S_a$ as depicted in Fig. 10. The increased amount of sintered powder particles lead to an increased arithmetic surface roughness $S_a$. In general, powder particles sinter to the build part surface when the adjacent melt pool is solidified before the powder particles are (fully) molten [22]. Due to the small melt pools generated in the contour within this study, short melt pool solidification times occur and, hence, surrounding powder particles are not fully molten. Due to the increased number of melt pools per unit length with an increasing pulse overlap, an increased number of powder particles per unit length is sintered to the surface.
3.4 Application to Build Part Geometry

Based on the results of the process parameter investigation, the transferability of the results to industrial applications has been investigated by fabrication of an adapted Francis turbine demonstrator as depicted in Fig. 11. As can be seen from photographs of the as-built state in Fig. 11a, b, the blades of the turbine manufactured with the cw exposure (a) reveal a more shiny surface with an increased waviness compared to the blades manufactured with the pw contour exposure, which show a homogenous surface topology without predominant surface structures (b). The honeycomb structured sealing of demonstrator (a) is of higher wall thickness than the honeycombs fabricated with the pw emission mode in the demonstrator (b). The analysis of the geometric deviations of the turbine blades show deviations >1 mm for some blades of the demonstrator (a), while deviations measured at the demonstrator (b) are
Fig. 11: Photographs of francis turbine manufactured with cw contour exposure (a) and pw contour exposure (b), corresponding geometric deviations for cw (c), and pw contour exposure (d), respectively.

comparatively lower (approx. <0.6mm). Moreover, turbine blades manufactured with the cw contour exposure reveal signs of excessive melting at the blade edge (see pronounced turbine edges in Fig. 11c). These geometric deviations might significantly affect the flow behaviour of the turbine but are, at the same time, difficult to remove.

The findings described indicate the importance of an energy input control into the powder bed at part areas with a limited heat dissipation like thin wall structures. Due to the higher energy input into the cw contour within this study, higher wall thicknesses of the honeycombs, increased thermal distortion of the turbine blades, and increased waviness of the blades’ surfaces due to larger melt pools in the build part contour are observed.

4. Conclusion

In the present contribution, the application of a pw contour exposure for manufacturing of geometries by LPBF has been investigated. Due to the discretization of the emitted laser energy by generating laser pulses, smaller melt pools are generated compared to continuous laser emission as mostly applied in conventional LPBF. An increased part accuracy is achieved if a discrete solidification of the adjacent melt pools is given. In this context, discrete solidification describes the completion of the solidification of a melt pool before the following melt pool is created by the next laser pulse. Smaller melt pools lead to reduced melt pool flows and, thus, reduced movement of powder particles into the melt pool compared to cw exposure. Therefore, the melt pool enlargement due to excessive melting, which is commonly observed in sharp angled contours using conventional cw LPBF, is reduced and the geometric accuracy is improved.

Apart from an improved accuracy, the contours fabricated by a pw exposure differ from those fabricated by a continuous exposure regarding the surface morphology. Due to the overlapping and discretely solidifying melt pools, a more homogenous morphology without predominant orientation is created, which differs from conventional surface morphologies in missing line-like structures known from the contour scanning vectors in cw exposure, which cause an increased waviness of the surface.

Under the condition of discretely solidifying melt pools, the process productivity is limited compared to cw exposure as the applicable scanning speed is limited by the solidification time of the melt pool. With an increased scanning speed, the pulse frequency has to be increased for a given spatial pulse overlap. In a first approximation, the processing region for a discrete solidification is surpassed if the pulse period is shorter than the solidification time of the melt pool. In general, the transition from a discrete to a continuous solidification occurs at scanning speeds significantly lower than those applied for a pw contour exposure. Hence, the local application of pw contour exposure only in critical part regions might both minimize productivity losses and ensure a high geometric accuracy.

Acknowledgements. The authors gratefully acknowledge funding of this research project by the German Federal Ministry of Education and Research within
the project “Industrialization of Digital Engineering and Additive Manufacturing (IDEA)” (Funding Grant Number 13N15001).

Funding. Open Access funding enabled and organized by Projekt DEAL.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Brinksmeier, E., Levy, G., Meyer, D., Spierings, A.B.: Surface integrity of selective-laser-melted components. CIRP Ann. 59, 601–606 (2010). https://doi.org/10.1016/j.cirp.2010.03.131
2. Braian, M., Jönsson, D., Kevci, M., Wennerberg, A.: Geometrical accuracy of metallic objects produced with additive or subtractive manufacturing: A comparative in vitro study. Dent. Mater. 34, 978–993 (2018). https://doi.org/10.1016/j.dental.2018.03.009
3. Gruber, S., Grunert, C., Riede, M., López, E., Marquardt, A., Brueckner, F., Leyens, C.: Comparison of dimensional accuracy and tolerances of powder bed based and nozzle based additive manufacturing processes. J. Laser. Appl. (2020). https://doi.org/10.2351/7.0000115
4. Calignano, F., Lorusso, M., Pakkanen, J., Trevisan, F., Ambrosio, E.P., Manfredi, D., Fino, P.: Investigation of accuracy and dimensional limits of part produced in aluminium alloy by selective laser melting. Int. J. Adv. Manuf. Technol. 88, 451–458 (2017). https://doi.org/10.1007/s00170-016-8788-9
5. Sadowski, M., Ladani, L., Brindle, W., Romano, J.: Optimizing quality of additively manufactured Inconel 718 using powder bed laser melting process. Addit. Manuf. 11, 60–70 (2016). https://doi.org/10.1016/j.addma.2016.03.006
6. Heigel, J.C., Lane, B.M.: Measurement of the melt pool length during single scan tracks in a commercial laser powder bed fusion process. J. Manuf. Sci. Eng. (2018). https://doi.org/10.1115/1.4037571
7. Kumar, P., Farah, J., Akram, J., Teng, C., Ginn, J., Misra, M.: Influence of laser processing parameters on porosity in Inconel 718 during additive manufacturing. Int. J. Adv. Manuf. Technol. 103, 1492–1507 (2019). https://doi.org/10.1007/s00170-019-06865-9
8. Li, S., Xiao, H., Liu, K., Xiao, W., Li, Y., Han, X., Mazumder, J.: Melt-pool motion, temperature variation and dendritic morphology of Inconel 718 during pulsed- and continuous-wave laser additive manufacturing: A comparative study. Mater. Des. 119, 351–360 (2017). https://doi.org/10.1016/j.matdes.2017.01.065
9. Clijsters, S., Craeghs, T., Buis, S., Kempen, K., Kruth, J.-P.: In situ quality control of the selective laser melting process using a high-speed, real-time melt pool monitoring system. Int. J. Adv. Manuf. Technol. 75, 1089–1101 (2014). https://doi.org/10.1007/s00170-014-6214-8
10. Geisen, O., Kersting, L., Masseling, L., Bogner, J.P., Schleifenbaum, J.H.: Additive manufacturing of honeycombs seal strips. In: Proc. of ASME Turbo Expo 2018, Oslo, Norway (2018)
11. Mumtaz, K.A., Hopkinson, N.: Selective laser melting of thin wall parts using pulse shaping. J. Mater. Process. Technol. 210, 279–287 (2010). https://doi.org/10.1016/j.jmatprotec.2009.09.011
12. Zaykowski, J.J.: Q-switched operation of microchip lasers. Opt. Lett. 1991, 575–577 (1991)
13. Haus, H.A.: Mode-Locking of Lasers. IEEE. J. Sel. Top. Quantum Electron. 2000, 1173–1185 (2000)
14. Caprio, L., Demir, A.G., Previtali, B.: Comparative study between CW and PW emissions in selective laser melting. J. Laser. Appl. (2018). https://doi.org/10.2351/1.5040631
15. Demir, A.G., Mazoloni, L., Caprio, L., Pacher, M., Previtali, B.: Complementary use of pulsed and continuous wave emission modes to stabilize melt pool geometry in laser powder bed fusion. Opt. Laser Technol. 113, 15–26 (2019). https://doi.org/10.1016/j.optlastec.2018.12.005
16. Demir, A.G., Colombo, P., Previtali, B.: From pulsed to continuous wave emission in SLM with contemporary fiber laser sources: effect of temporal and spatial pulse overlap in part quality. Int. J. Adv. Manuf. Technol. 91, 2701–2714 (2017). https://doi.org/10.1007/s00170-016-9948-7
17. Kim, J., Ji, S., Yun, Y.-S., Yeo, J.-S.: A Review: melt pool analysis for selective laser melting with continuous wave and pulse width modulated lasers. Appl. Sci. Converg. Technol. 27, 113–119 (2018). https://doi.org/10.15777/ASCT.2018.27.6.113
18. Bruna-Rosso, C., Caprio, L., Mazoloni, L., Pacher, M., Demir, A., Previtali, B.: Influence of temporal laser emission profile on the selective laser melting (SLM) of thin structures. Lasers in engineering, pp. 161–182 (2020)
19. Mumtaz, K., Hopkinson, N.: Top surface and side roughness of Inconel 625 parts processed using selective laser melting. RPJ 15, 96–103 (2009). https://doi.org/10.1109/13552540910943397
20. Oerlikon, A.M.: Additive manufacturing 718 nickel alloy (2021)
21. Routoulas, T.: grabcad.com/library/francis-turbine-fan, Accessed 12 Feb 2021
22. Matthews, M.J., Guss, G., Khairallah, S.A., Rubenchik, A.M., Pendar, P.J., King, W.E.: Denudation of metal powder layers in laser powder bed fusion processes. Acta Mater 114, 33–42 (2016). https://doi.org/10.1016/j.actamat.2016.03.017

Publisher’s Note. Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.