ArcelorMittal

Global Research and Development

May 2023

Novel approach to increase LPBF productivity

Sensitivity analysis of printing parameters for LPBF systems and novel approach to increase productivity

Introduction

Laser Powder Bed Fusion (LPBF) is the most widely used additive manufacturing technology for producing metal parts, layer-by-layer. Given the significant capex involved in installing an LPBF machine, increasing the productivity of the process is a critical factor to significantly reducing the production costs of the additively manufactured parts.
A common approach to try to define the most productive printing conditions for a given material is to print density cubes under different conditions and to create maps of density versus volumetric energy density (VED). Sufficient density is taken as an indicator of quality while the lowest VED is expected to give the fastest build rate.

$$VED = \frac{P}{V * HD * L}$$

P = Power of the laser [W]: a characteristic of the installed equipment.

HD = Hatch distance [mm]: the distance between adjacent laser scans in the LPBF process. A smaller hatch distance gives a better surface finish/part quality, but the larger number of laser scanning passes negatively impacts productivity.

V = Scan speed [mm/s]: the velocity of the laser across the powder bed. Increasing the velocity leads to higher productivity but can also decrease the print quality if the laser is not able to melt all the powder.

L = Layer thickness [mm]: the depth of the powder layer per cycle of the process. Thicker layers can be printed faster than thinner layers, but thicker layers require more precise control of the laser and can lead to lower quality parts. The resolution needed for the part application will be a limiting factor for the layer thickness selection.

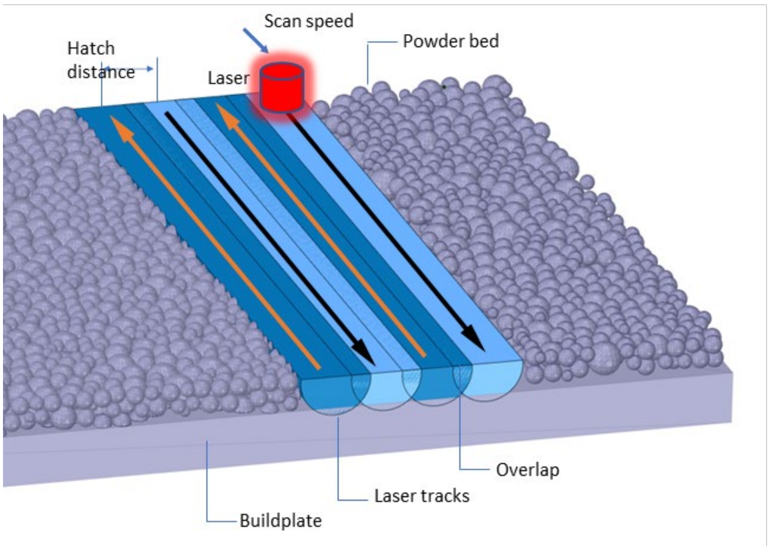


Figure 1 – LPBF sketch at the layer level.
Source: ArcelorMittal Global R&D.

However, ArcelorMittal's experience is that a VED/density approach is not a reliable indicator of LPBF performance if the final goal is to achieve the most productive printing parameters for a specific case. Including other factors such as layer topology (the part to be printed) and the printing strategy, a new methodology for LPBF process optimization is proposed, which is the one that ArcelorMittal now uses when assessing parts for serial production. This publication is an example of this methodology applied to a real-life production part.

Printing strategy: the pattern of laser movements over the powder bed as successive layers of the part are laid down during production. Several different strategies exist to distribute the laser scanning vectors, including chessboard, meander, stripes.

Complementary to the printing parameters mentioned above, one factor has a huge influence over the total productivity of any LPBF system, namely the number of lasers available. Given that the number of lasers also increases the complexity of the overall problem, due to heat flux implications, this publication only considers an LPBF with a single laser.

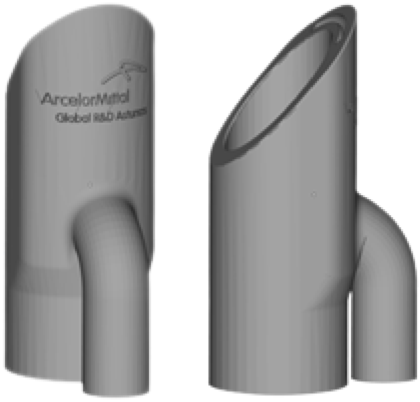
Motivation

Since 2018, ArcelorMittal R&D has been exploring the potential of additive manufacturing to optimise the production of spare parts, often critical, and consumables used in ArcelorMittal's steelmaking operations. These parts were originally designed from a conventional manufacturing perspective, which often resulted in complex assemblies due to the limitations of the processes. The research approach was defined along two main action lines. The first was to replace or repair parts where the lead time and cost of additive manufacturing were competitive with traditional production methods. The second was to go deeper into application areas and to identify (sub-)assemblies which could be re-designed to benefit from some, or all, of the advantages of additive manufacturing, namely part consolidation, light-weighting, improved performance, increased functionality and material savings.
Initially, few applications could be identified where LPBF could be competitive in size and cost to alternative supply options. Subsequently, a dedicated research line was started to increase the productivity and quality of LPBF by adjusting the process parameters and printing strategies. The goal was to test the limits of LPBF and identify whether sufficient cost improvement could be made to justify the technology's use in a wider range of applications. Given that processing parameters change with the material being processed, the work covered those steel grades that are most commonly used in additive manufacturing, namely 316L, 17-4PH, M300 and H13.
While the first approach was to use the VED/density analysis, it soon became clear that this would not lead to sufficient productivity gains. Also, it did not address issues such as reducing residual stresses, improving surface roughness, or enhancing mechanical properties. Other factors, but especially the printing strategy, were found to be influential in achieving the maximum productivity in terms of build rate in cubic centimetres per hour.
Based on these findings, a new methodology for LPBF process optimisation is proposed, which is the one now being used by ArcelorMittal to assess parts for serial production.

Business case

The part discussed here is an example of a spare part which could benefit from a redesign, made possible by additive manufacturing. The part is a nozzle which provide a protective gas coverage over a measurement device within an ArcelorMittal steelmaking facility. A first iteration of this part, in 2018, resulted in a better design than the original part from the plant. This preliminary design {see patent [1]}, achieved a significant improvement in the replacement periodicity of the measuring device's lens, as the improved gas-cover protected the lens from fumes and projections from the steelmaking process.
In 2021, drawing on improved LPBF process knowledge as well as better understanding of design limitations, the nozzle was re-designed again {see patent [2]}. Beyond functional performance, the new design (Figure 2) considered the minimisation of support structures, for faster printing and material savings, as well as designing the angles of the internal channels to avoid any postprocessing. The nozzles are designed to be printed using 17-4PH.

[1] Diaz Vaquero, Sheila. Device for protecting a means for measuring a parameter of a distant element, and method for making the device. WO2018/122573A1·2018-07-05.
[2] Diaz Vaquero, Sheila. Device for protecting a means for measuring a parameter of a distant element, and method for making the device. WO2021/099821A1·2021-05-27.



Main data:
X: 42.00 mm
Y: 64.5 mm
Z: 114.25 mm
Volume: 57.284 cm^3

Figure 2 – Protection nozzle geometry and its main geometrical data for LPBF process.
Source: ArcelorMittal.

For the new part geometry, a packing optimization was carried out for one of the LPBF machines that ArcelorMittal R&D operates. The result is a build job composed of 24 nozzles within the build plate with a minimum gap distance of 2.5 mm between parts for safety during the printing. The packing density of this build job is 19,72%, which is a typical packing density for serial production (Figure 3).

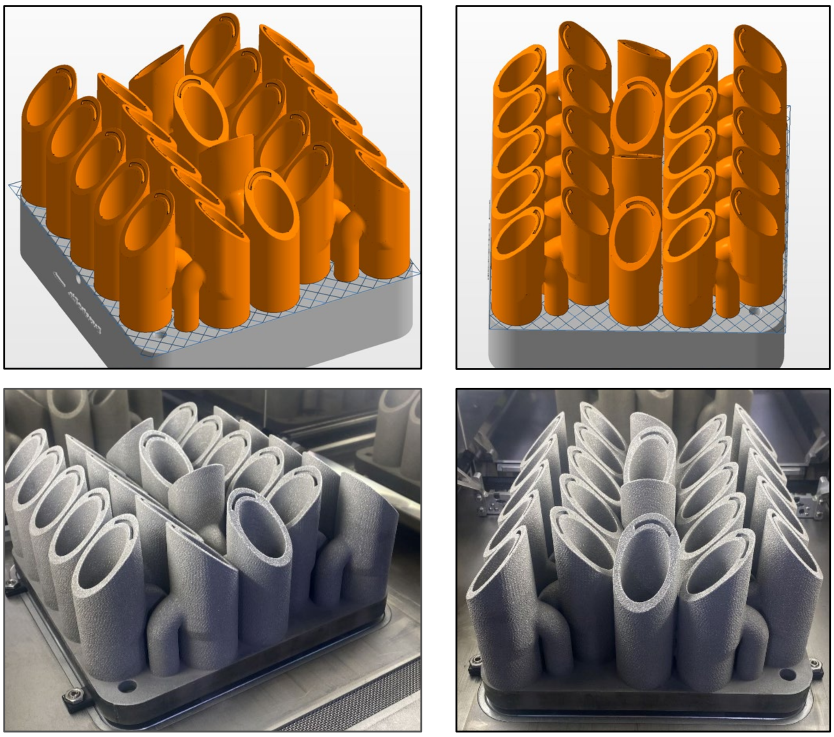


Figure 3 – Nozzle layout for LPBF machine in ArcelorMittal Global R&D. Digital model in top row. Actual printed layout in bottom row.
Source: 2022 ArcelorMittal.

Having designed the part and the build job layout, the most important question is which printing parameters are the most suitable?
Using the standard "out-of-the-box" parameters of the LPBF used in this case would give a build rate of 12 cm^3/h. Given that these parameters are not specific to the part design, they can only provide a reference against which to demonstrate the importance of optimising printing parameters.
For 17-4PH, a design of experiments (DOE) to create density cubes under a wide range of printing conditions was performed. The LPBF machine of this study has 4 lasers of 500 W maximum power each but, for homogeneous printing, not more than 450 W was used to ensure consistent laser beam quality.

From the DOE, Figure 4 is the resultant mapping of VED vs density, where each point represents a cube. All the cubes are over 99.5% dense by the Archimedes density method. This density characterisation was verified for each cube with a cross section in order to calibrate certain Archimedes parameters.

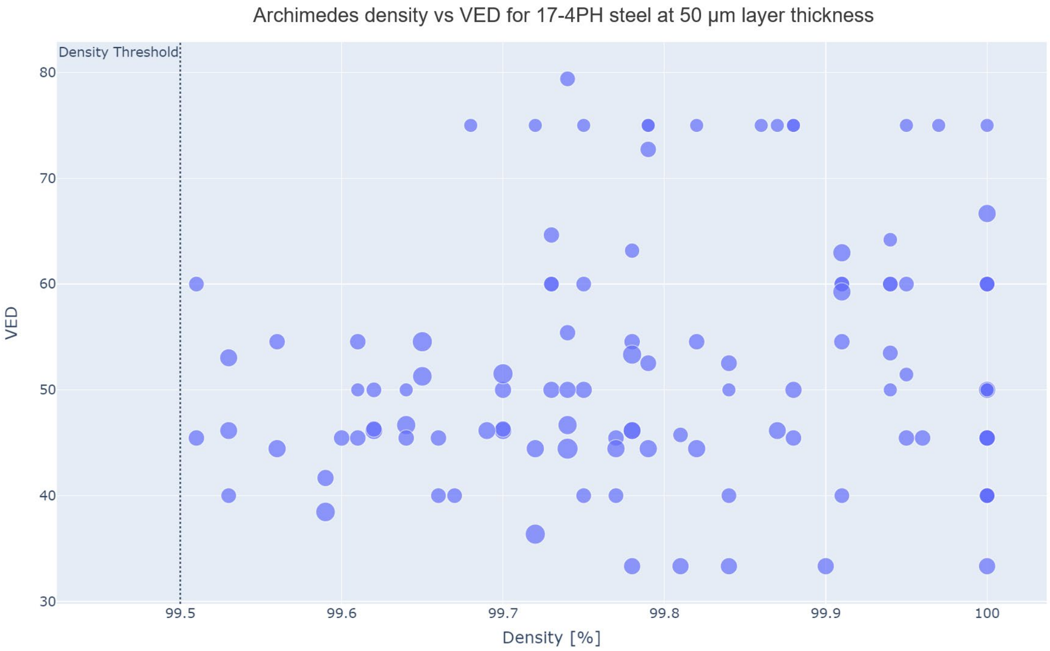


Figure 4 – Parameter set of cubes over 99.5 % density, showing the volumetric energy density [VED] value for 17-4 PH at 50 µm layer. Source: ArcelorMittal 2022.

From Figure 4, it is clear that there are several parameters sets which are suitable for the application. The classic approach would be to select one of the operational parameter sets providing the lowest VED. This would be the highest productivity option if all the parameters in the VED formula had an equal impact on productivity. Unfortunately, this is not the case. While the parameter with the highest influence on productivity is layer thickness [µm], the relative influence of hatch distance [µm] and printing speed [mm/s] is not clear. The main point for an optimal production of the parts is to understand how the influence of these parameters on productivity can be parametrized. Considering that LPBF manufacturing behaviour is inherently based on thousands of individual laser movements (vectors) per layer, this vector distribution (printing strategy) can potentially play a very important role in the parametrization.

Incorporating the printing strategy sensitivity into the parameter optimization step creates a multivariant-problem which hinders direct parameter selection but is necessary and worthwhile in the case of series production. The sensitivity analysis is conducted purely numerically, which is possible thanks to a computer model that precisely reproduces the LPBF machine build times. Also, while most LPBFs use one of two typical printing strategies, for the purpose of this disclosure, more strategies have been analysed to show the scale of influence that vectorisation can have in a real-world build job.

It should be mentioned that in Figure 4, not all the parameter sets are under the same printing strategy, but any effect that this may have is considered minimal given the cube size employed in the DOE.
Brief reminder that this study only considers the single-laser case. The effect in a multi-laser case would be even more pronounced.

Sensitivity Analysis for the Business Case

Sensitivity analysis can identify the parameters with the greatest impact on a particular output or performance metric. In ArcelorMittal, an approach based on parameter sensitivity is used in combination with the printing strategy, to determine the parameter set to maximise the LPBF productivity when assessing parts for serial production. The charts below are specific to the part design and packing layout of this specific business case.

Meander Zig-Zig printing strategy

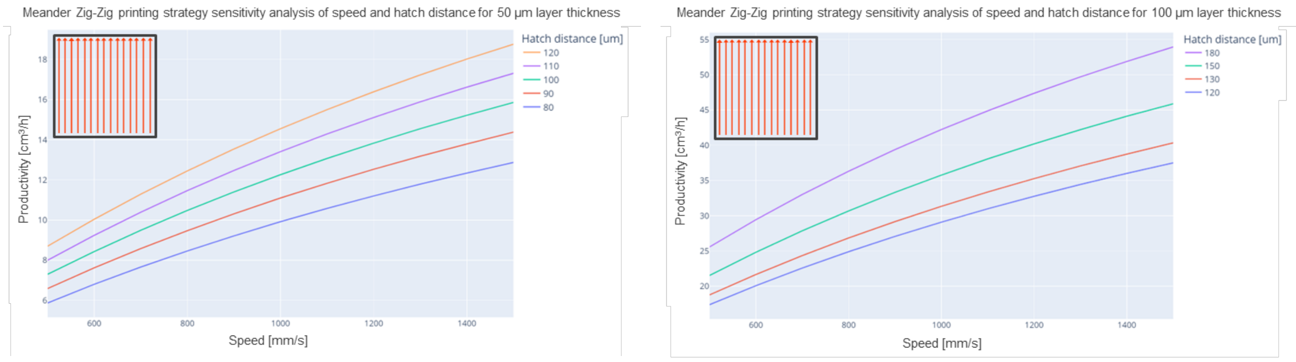


Figure 5 – Meander Zig-Zig printing strategy sensitivity analysis. Productivity against scan speed and hatch distance map for two different layer thickness: Left [50 µm] and Right [100 µm]. Source: ArcelorMittal Global R&D 2023.

Meander Zig-Zag printing strategy

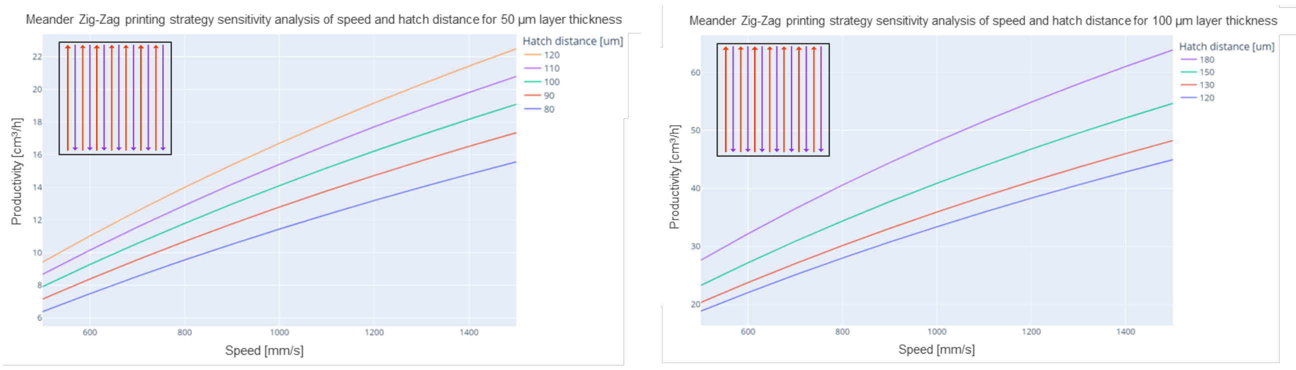


Figure 6 – Meander Zig-Zag printing strategy sensitivity analysis. Productivity against scan speed and hatch distance map for two different layer thickness: Left [50 µm] and Right [100 µm]. Source: ArcelorMittal Global R&D 2023.

Chess printing strategy

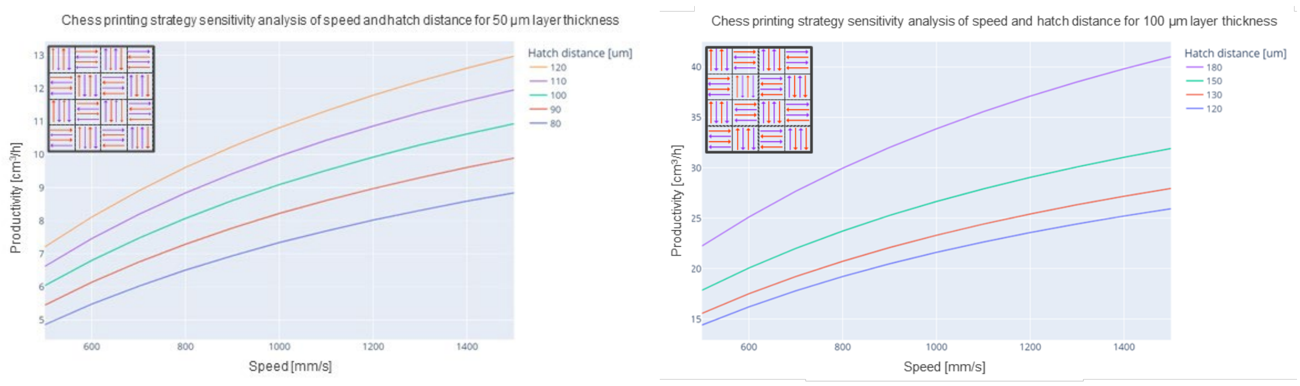


Figure 7 – Chess printing strategy sensitivity analysis. Productivity against scan speed and hatch distance map for two different layer thickness: Left [50 µm] and Right [100 µm]. Source: ArcelorMittal Global R&D 2023.

Stripes printing strategy

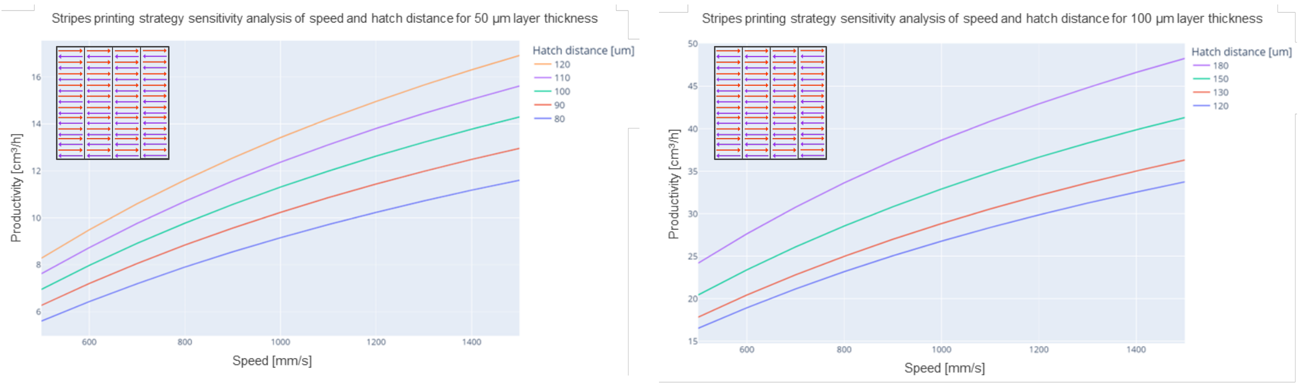


Figure 8 – Stripes printing strategy sensitivity analysis. Productivity against scan speed and hatch distance map for two different layer thickness: Left [50 µm] and Right [100 µm]. Source: ArcelorMittal Global R&D 2023.

As can be seen in Figures 5 through 8, irrespective of the printing strategy chosen, the relationship between the laser scan speed, hatch distance and the productivity of a one-laser system is non-linear. This non-linearity is the reason that the classic approach of selecting the lowest VED does not necessarily give the highest productivity. To demonstrate this, consider Figure 9, where three arcs have been added to the Meander Zig-Zag chart shown in Figure 6, with each arc representing a different level of laser power. The points on all three arcs have the same VED value, but widely different levels of productivity.

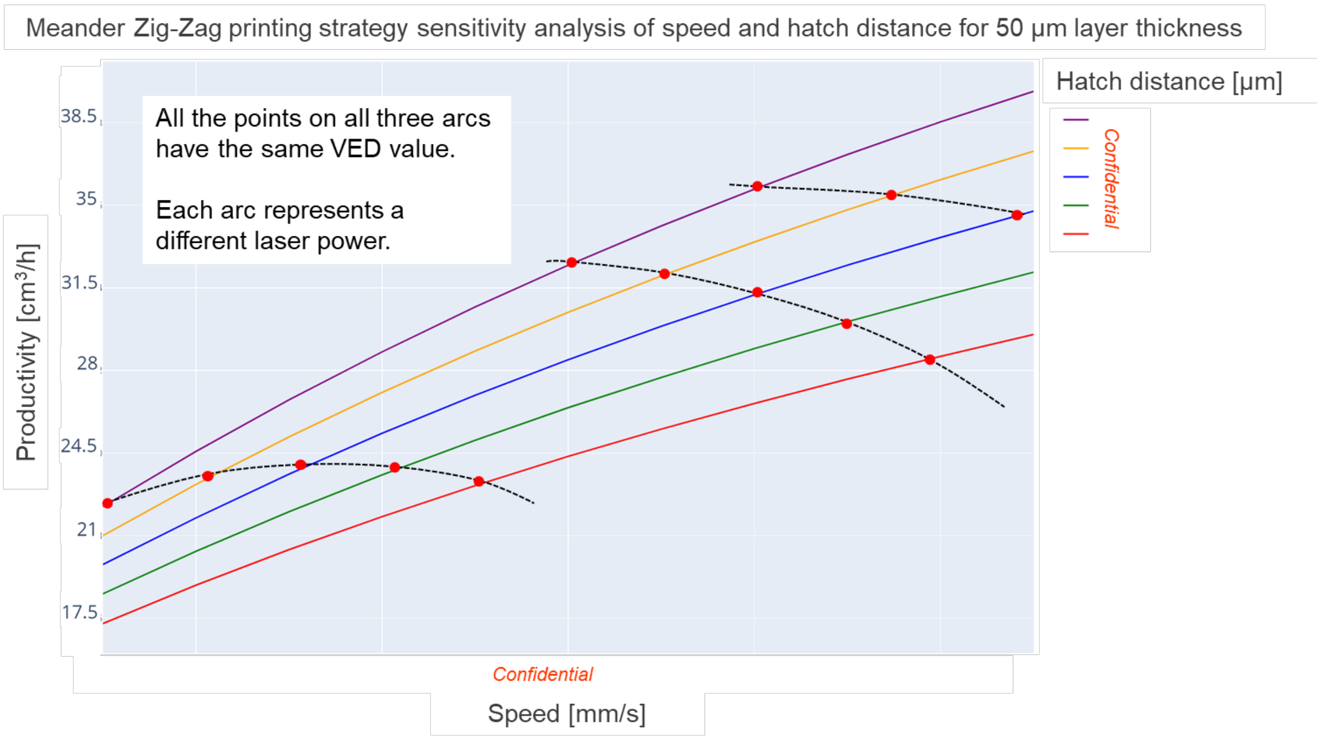


Figure 9 – Productivity against scan speed and hatch distance map with arcs of similar VED at different laser powers. Source: ArcelorMittal Global R&D 2023.

Figures 5 through 8 also highlight that the choice of printing strategy also plays a crucial role in maximising LPBF productivity for a specific part. For this specific business case, Figure 10 shows that each printing strategy has a different inherent correlation of scan speed and hatch distance with productivity. For production of the nozzle build plate, a Meander Zig-Zag strategy can clearly give the highest productivity rate.

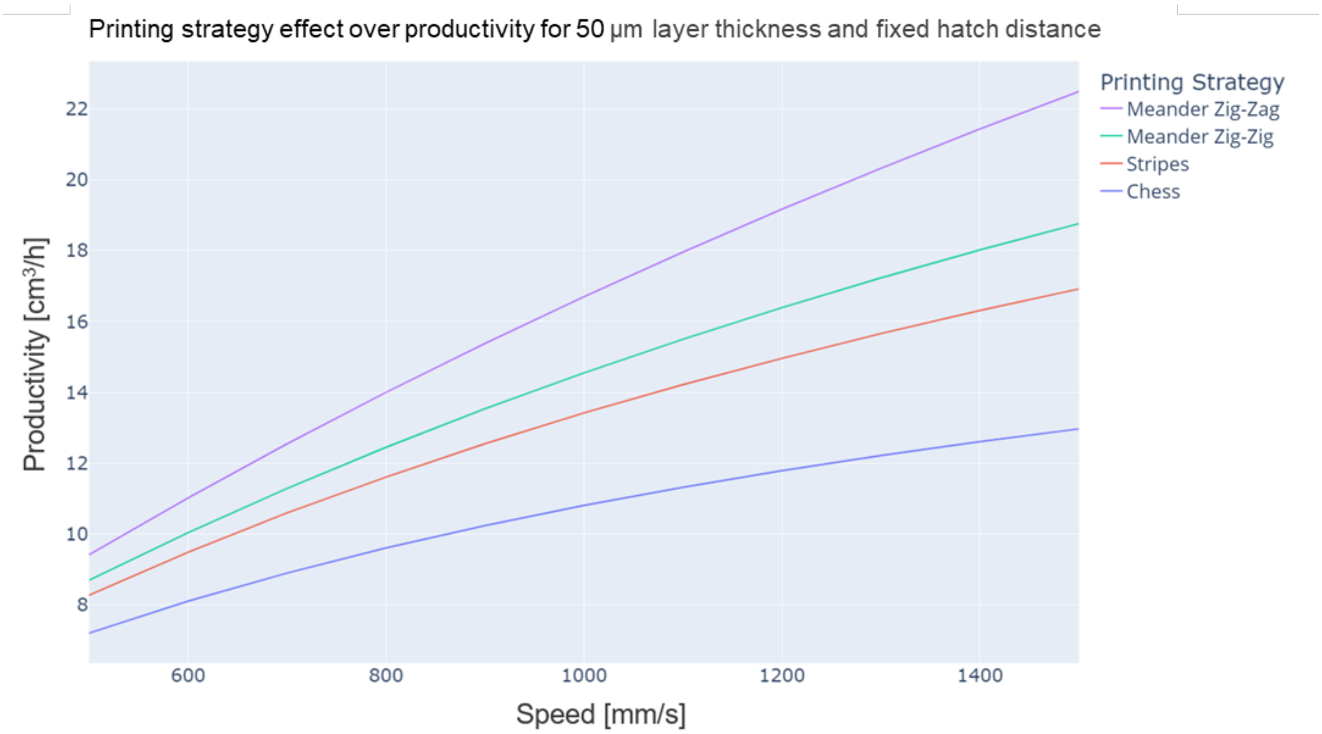


Figure 10 – Sensitivity to different printing strategies under the same layer thickness and hatch distance that shows the effect over the productivity and the scalability in the process speed. Source: ArcelorMittal Global R&D 2023.

Having selected the best printing strategy, the printing parameters giving the highest productivity for this build can be selected from the sensitivity analysis chart for the chosen layer height. See Figure 11.

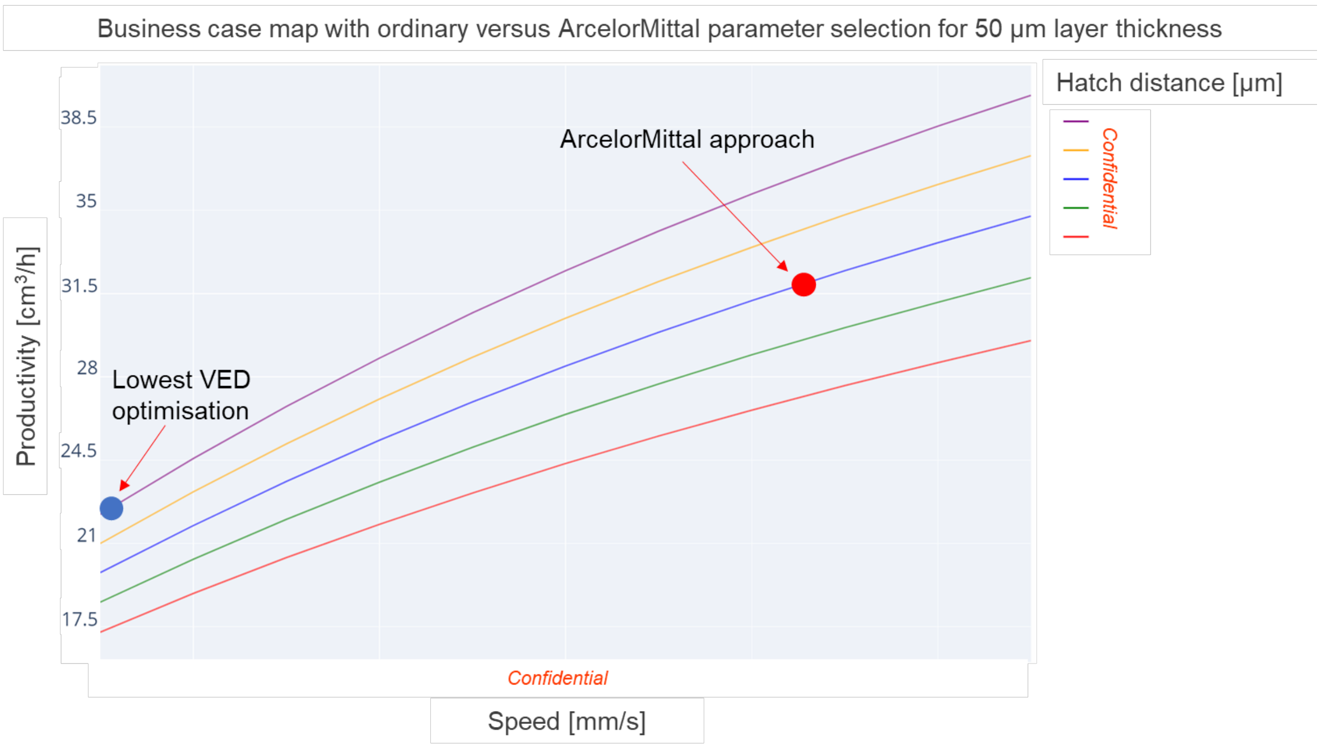


Figure 11 – Shows the build productivity for the ArcelorMittal optimised processing conditions compared to the VED/density approach, using a Meander Zig-Zag strategy. Source: ArcelorMittal Global R&D.

Taking the VED/density optimisation mapping, shown previously in Figure 4, and incorporating the sensitivity analysis data as a high-quality metric of productivity for this specific build case, gives Figure 12:

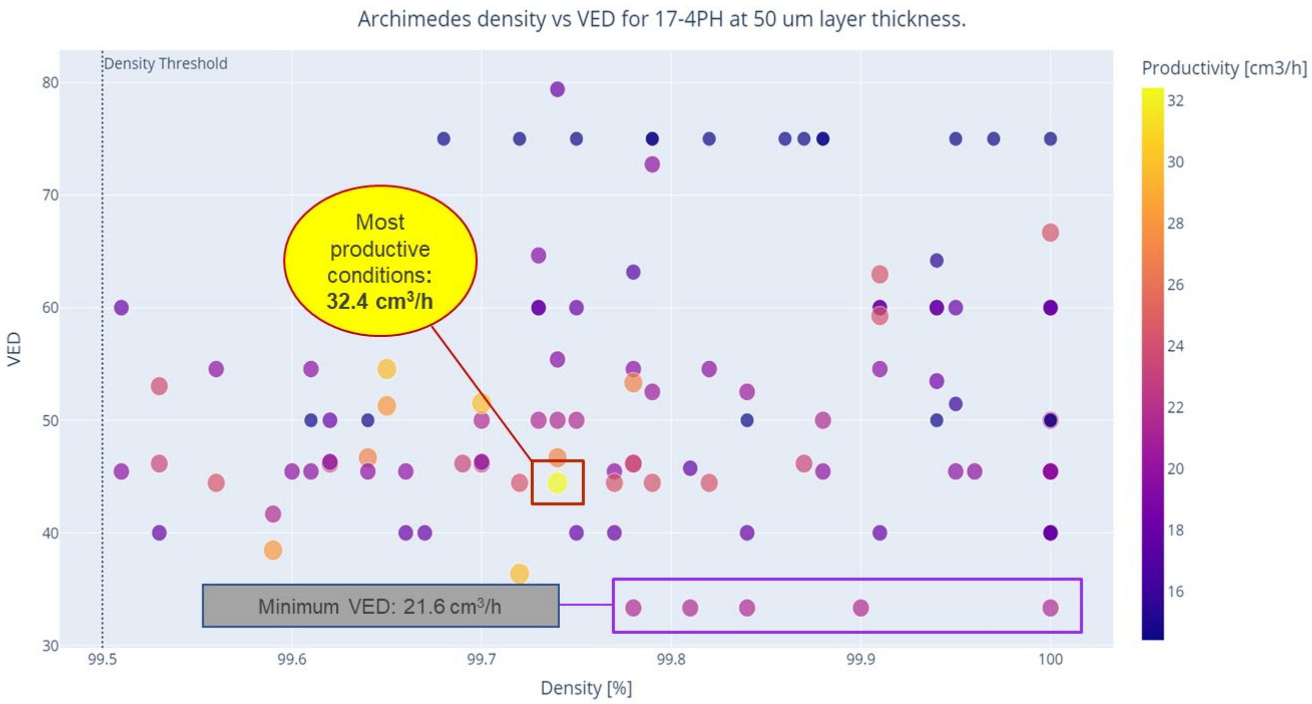


Figure 12 – Parameter set developed for 17-4 PH steel at 50 µm layer thickness. Most productive parameter combination found due to the proper analysis. Source: ArcelorMittal Global R&D 2023.

Compared to the "out-of-the-box" productivity (12 cm³/h), the classic approach to parameter optimisation, choosing the lowest VED, achieves a significantly higher build rate of 21.6 cm³/h.

While this demonstrates the importance of optimising printing parameters, the most productive set of processing parameters for our business case are not one of the sets with the lowest VED.

By considering the printing strategy sensitivity analyses, for our specific build job, a build rate of 32.4 cm³/h can be achieved. This is a further 50% improvement on the VED/density approach.

Conclusions

Productivity is the most significant issue in additive manufacturing. The classic approach to improve LPBF productivity, selecting the parameters with the lowest VED, delivers significantly better layer build rates than the out-of-the-box parameters of the machine. However, two factors constrain this approach from actually identifying the optimal printing conditions for a part, the inherent non-linear relationships between the parameters and the choosing the right printing strategy for the part design/packing density.
This publication presented a new approach to maximise the productivity of a single-laser LPBF by combining the volumetric energy density approach with a sensitivity analysis of printing strategies. This approach identifies the best printing parameter set for the specific real-world spare part to be printed. In this approach, each material will have its own optimum "process window", so a complete, and broad design of experiments is needed for each material.
In an example business case, a spare part is printed on a single-laser LPBF. With 24 parts fitting on the build plate, the packing density of the build job was just under 20% which is a normal level for serial production. Compared to the typical approach of VED/density mapping, the novel approach increased the average build rate per layer by 50%.

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