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The Effects of Laser Misalignments in Multi-Laser Powder Bed Fusion Manufactured Inconel 718

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Abstract

This study investigates the influence of multi-laser process parameters on the porosity and alignment of Laser Powder Bed Fusion (LPBF) manufactured Inconel 718. The LPBF process allows for the fabrication of complex geometries with high material efficiency. However, the quality of the manufactured parts, particularly porosity and alignment, are significantly affected by the process parameters used during printing. In this study, we focus on multi-laser stitching, a technique that involves the use of multiple lasers to manufacture a single part. Process parameters were systematically varied during the printing of jailhouse type specimens, including build direction, laser power, scanning speed, and alignment, to analyze their effects on the resulting porosity.

We observed that certain combinations of process parameters can significantly reduce porosity, leading to improved mechanical properties. This research provides insights for optimizing the LPBF process for the manufacturing of Inconel 718, by presenting a correlation between process parameters and resulting porosity.

Introduction

Nickel-based superalloys, particularly Inconel 718 (IN718), have gained considerable attention due to their superior strength, versatility, and resistance to corrosion even at elevated temperatures up to 650°C. The exact composition ranges from 50-55% nickel, 17-21% chromium, 4.8-5.5% niobium, 2.8-3% molybdenum, 0.65-1.15% titanium, 1% cobalt, with the remainder being iron and aluminum [1].

Laser Powder Bed Fusion is an additive manufacturing technique that uses a high-power laser to fuse metal particles on a bed of powder metal layer by layer to create models that would be impossible to fabricate through machining. In recent years, the introduction of multiple lasers to these machines has become more prominent in the industry. This technique offers several advantages over single-laser LPBF, including increased productivity by having 2-4 lasers print a single part, or each laser work on its individual part simultaneously. Also, the ability to manufacture larger parts by providing a larger optical range. However, having more lasers means more variables that will have to be controlled, for this reason, Multi-laser LPBF (M-LPBF) introduces unique challenges, including microstructural inconsistencies, laser alignment, porosity, and variations in printed vs nominal dimensions. When it comes to laser alignment, each laser will have to be calibrated with precision to achieve a "perfect" alignment, while improper calibration will lead to lasers having a gap, overlap, or shear misalignment (Fig. 1).

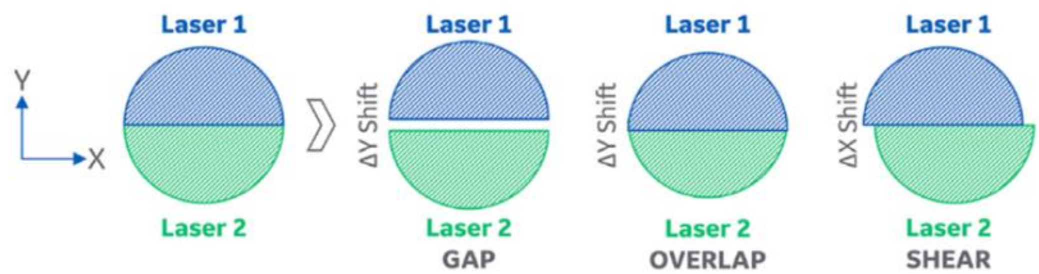


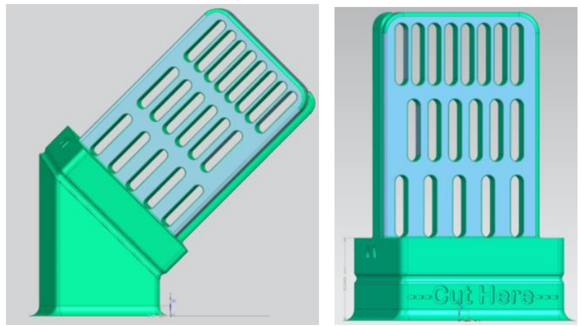
Figure 1. Delta X and Delta Y laser misalignment build conditions (GE Research)

In the context of M-LPBF, "stitching" refers to the process where multiple lasers are used to manufacture a single part in a way that is equivalent to using a single laser, and stitch region is the part of the build where two or more lasers interact. If not done correctly, it can lead to inconsistencies in the resulting part, such as potential material defects and variations in porosity or dimensions. Therefore, understanding and optimizing the stitching process is crucial for improving the quality of M-LPBF manufactured parts [3]. This research will concentrate on the analysis of porosity and measurement of dimensions in M-LPBF manufactured Inconel 718 under different multi-laser stitching conditions, by examining the occurrence of voids in the material that can weaken the mechanical properties of the fabricated parts and measuring critical dimensions through optical microscopy.

Materials and Methods

M-LPBF Test Artifacts

Jailhouse type specimens were printed from Inconel 718 powder using a Concept Laser M2 LPBF machine (GE Additive, Germany), equipped with two lasers. Two build directions were considered for the fabrication of the specimens, vertical and angled at 45°, each with three levels of thin walls measuring 500 µm at the top, 1 mm in the middle, and 2 mm at the bottom (Fig. 2). Additionally, induced stitch variations are introduced by intentional laser misalignment of 150-200 µm, with the purpose of identifying the most impactful stitch parameters that will influence material quality.

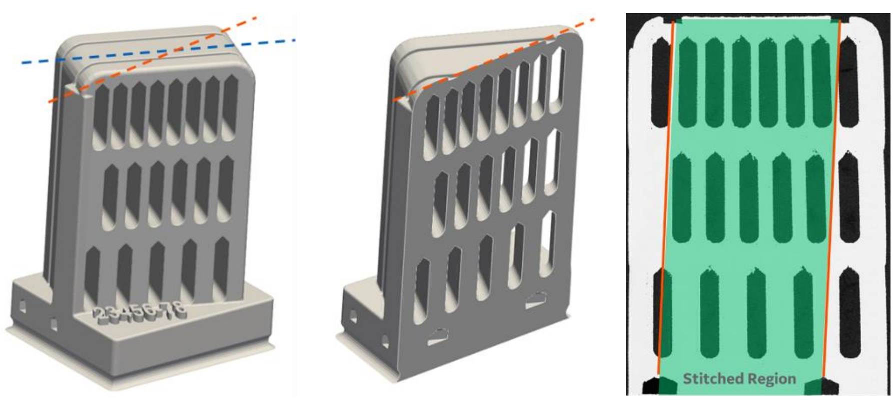


(a) (b)

Figure 2. CAD models of jailhouses in (a) angled and (b) vertical build directions.

Specimen preparation

Two features were added onto the CAD model that delineate the stich region, with the purpose of easily identifying the area of interest. The features are two parallel grooves that mark the stitch zone (blue line in Fig. 3a) on the lateral and top walls of the jailhouse, and two fiducial marks on the bottom of the jailhouse. After printing, an angled cut (red line in Fig. 3a) was performed using a Brillant 220 precision cutter (ATM, Germany) that would allow for characterization of entire stitch zone width. The resulting samples had an exposed cross-sectional angled plane (Fig 3b) where the stich region can be identified using the previously mentioned fiducial marks. The specimen variant of vertical build direction with gap misalignment was unfortunately destroyed during the cutting process, to mitigate impact on data, unstitched specimens were included for comparison purposes



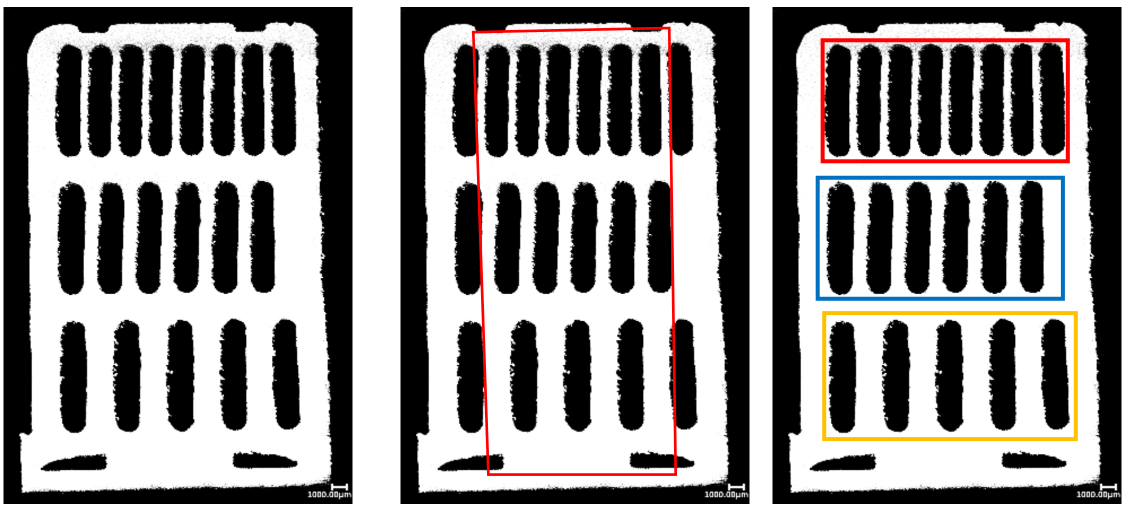
(a) (b) (c)

Figure 3. Cutting process for porosity analysis of stitch region. (a) Angled cut & stitch region lines (b) Angled cross section (c) Delineated stitched region of cross section

Samples were cold mounted in epoxy, grinding and polishing were performed using a Saphir 530 grinding and polishing machine (ATM, Germany). The process began with 120 grit paper, followed by 240, 320, 600, and 1200 grit. Afterward, manual polishing was carried out to achieve a mirror finish. The sequence involved using a sigma pad with 6 µm diamond suspension, followed by a sigma pad with 3 µm suspension, a zeta pad with 1 µm suspension, and finally an omega pad with 0.1 µm Eposil fumed silica.

Porosity Analysis

As-polished stitched images (Fig. 4a) were captured at a magnification of x50 with a VHX-7000 digital optical microscope (Keyence, Japan). Using the Auto area measurement tool of the Keyence software, porosity analysis was performed on specimens in the full stich region (Fig. 4b) and in each thin wall level (Fig. 4c). Measurement yields % ratio of total porosity area to area analyzed.



(a) (b) (c)

Figure 4. Digital microscopy cross sectional image of jailhouse and analysis per region (a) full and (b) by level

Dimension Measurement

In order to enhance our characterization data, we conducted dimensional measurements of the features in the printed samples, which can be affected by build direction and degree of misalignment. Using the Keyence measurement software, dimensions were recorded on two different planes of the jailhouse and compared to nominal CAD dimensions. First, on the same plane as the porosity analysis, the width of five points along the thin walls in the top level was measured by tracing horizontal parallel lines that ran across all seven thin walls. To create relevant measuring points, the first reference line was traced from the lowest point in the curve of the leftmost hole, to the same point on the opposite side, marked by a cross in Fig. 5. Then using the nominal CAD length of 7.5 mm (top to bottom) divided by half to yield the theorical midpoint of 3.75 mm to have the first point of measurement. Two more horizontal lines were traced with an offset of 1.25 mm apart from each other in the top and bottom directions, providing four more measuring points, and the intersection point from the horizontal lines with each side of the walls was measured as the width of the thin wall across different heights.

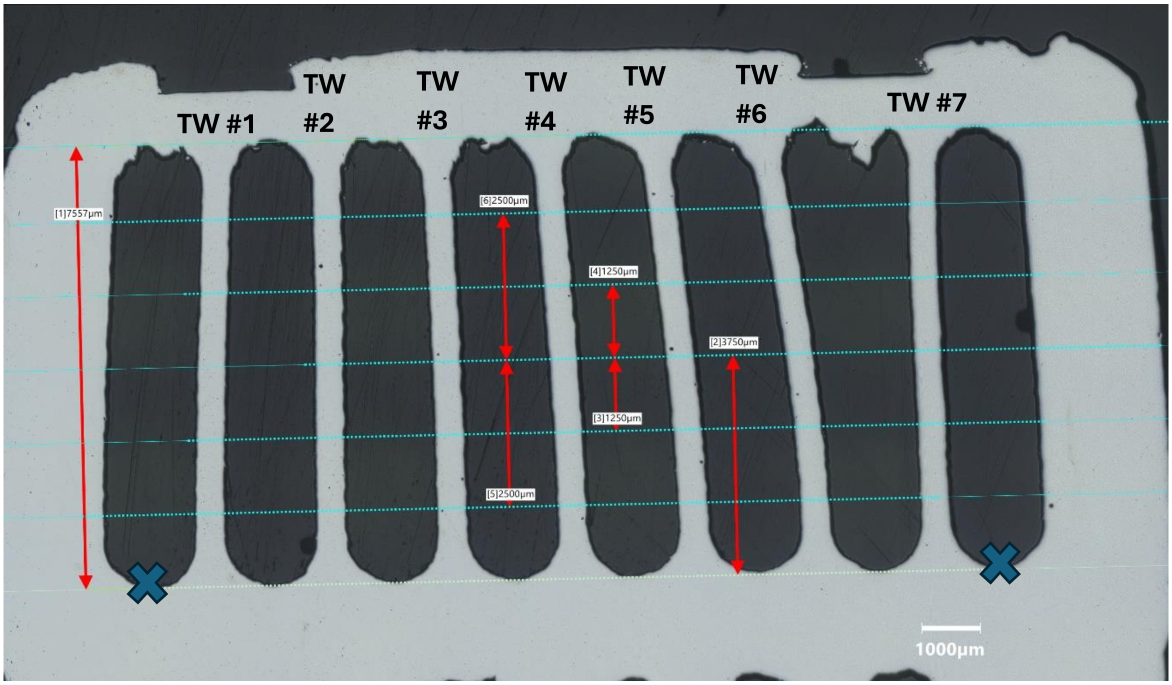


Figure 5. Horizontal reference lines for thin wall width measurement

The second dimension was measured on the same location using a top view plane, to achieve this a second cut had to be performed across the thin walls to measure length rather than width. A reference line was traced along the grooves from the outer walls (marked by arrows), and 3 parallel lines per thin wall were traced with respect to the reference line.

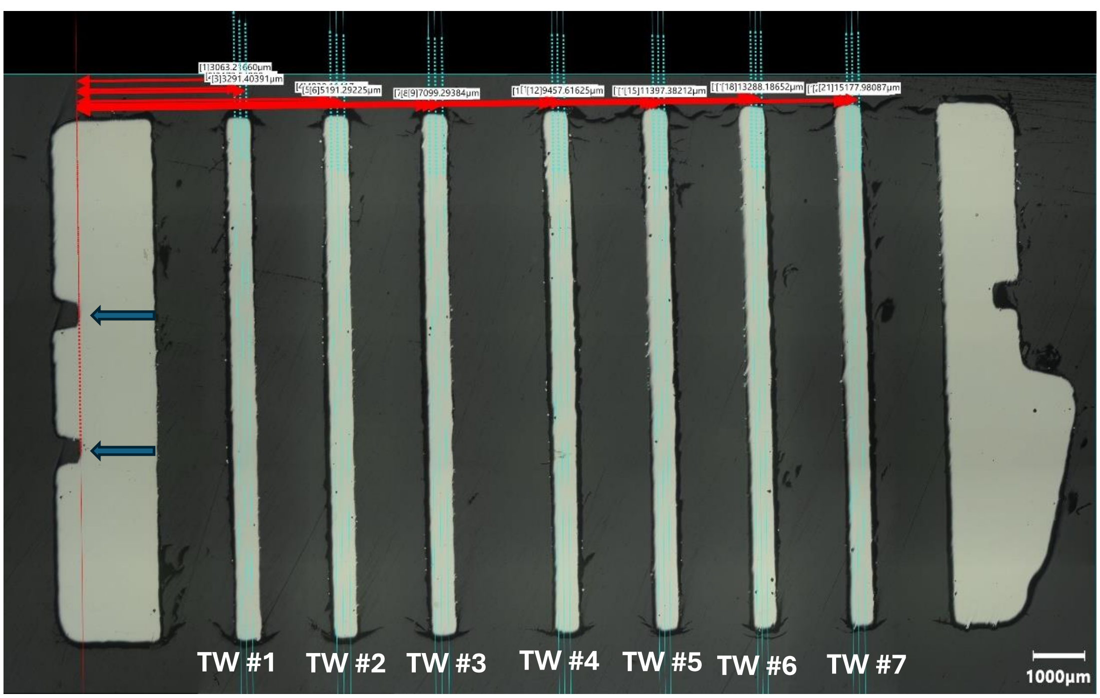


Figure 6. Thin wall cross section for length measurement

Results and discussion

Porosity

Table 1 displays the results of the porosity analysis, which determined that the jailhouse variant with the highest amount of porosity recorded is angled build direction + gap misalignment, with 0.236%. Higher porosity in the gap misalignment specimen may be due to, but not solely attributed to, decreased laser power intensity [4].

Misalignment	Build Direction	Range	Area % Ratio
Shear	Vertical	Full	0.055
		Top	0.085
		Middle	0.056
		Lower	0.021
	Angled	Full	0.068
		Top	0.088
		Middle	0.050
		Lower	0.032
Overlap	Vertical	Full	0.010
		Top	0.005
		Middle	0.035
		Lower	0.013
	Angled	Full	0.098
		Top	0.051
		Middle	0.070
		Lower	0.043
Gap	Angled	Full	0.236
		Top	0.070
		Middle	0.128
		Lower	0.295
Unstitched (one laser)	Vertical	Full	0.049
		Top	0.040
		Middle	0.053
		Lower	0.086
	Angled	Full	0.023
		Top	0.025
		Middle	0.036
		Lower	0.012

Table 1. Porosity analysis results

Although comparisons between each misalignment variant can be made, no formal correlation can be interpreted from the results of vertical vs angled build directions, as difference in the results are statistically insignificant. This led us to develop other characterization methods, such as dimension measurements.

Width Measurements

Figure 7 presents the result of width measurements of the top-level thin wall of a vertical build direction + 150 µm shear misalignment, and a vertical build direction + 200 µm shear misalignment. This indicated that thin walls located inside the stitch regions (#3,#4,#5) present greater thickness compared to those outside this region, however, when comparing to the 500 µm nominal CAD parameters, thin walls outside the stitch region (#1,#2,#6,#7) come closer the nominal dimensions.

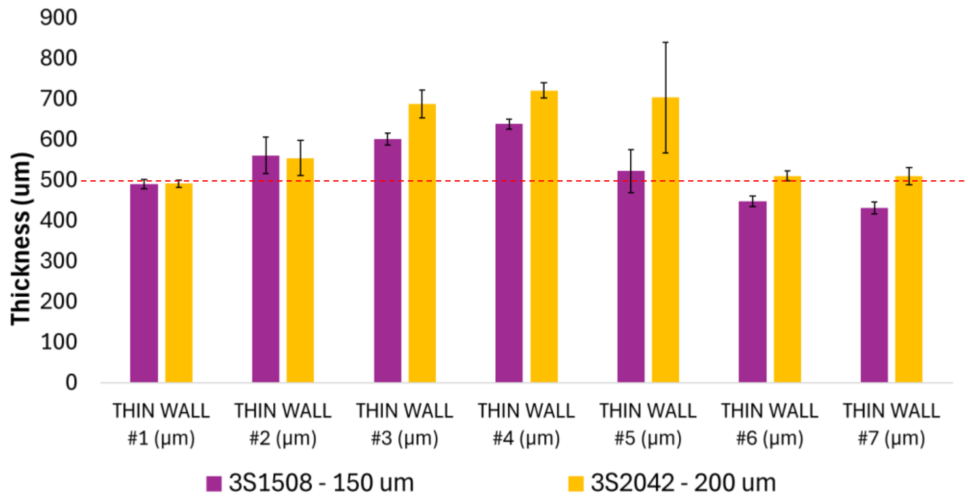


Figure 7. Width measurements results across thin walls.

Length Measurements

Figure 8 presents the result of length measurements of the top-level thin wall of a vertical build direction + 150 µm gap misalignment, and an angled build direction + 150 µm gap misalignment. This comparison was made to analyze how the gap misalignment can impact the resulting geometry, and as expected, length of the thin walls was close to 10150 µm since the nominal length is 10000 µm and adding the 150 µm in laser gap is what is represented in the results. Vertical jailhouse came closer to the expected result of 10150 µm in length, this result suggests that variations in geometry due to gap misalignment in vertical build directions may be easier to predict.

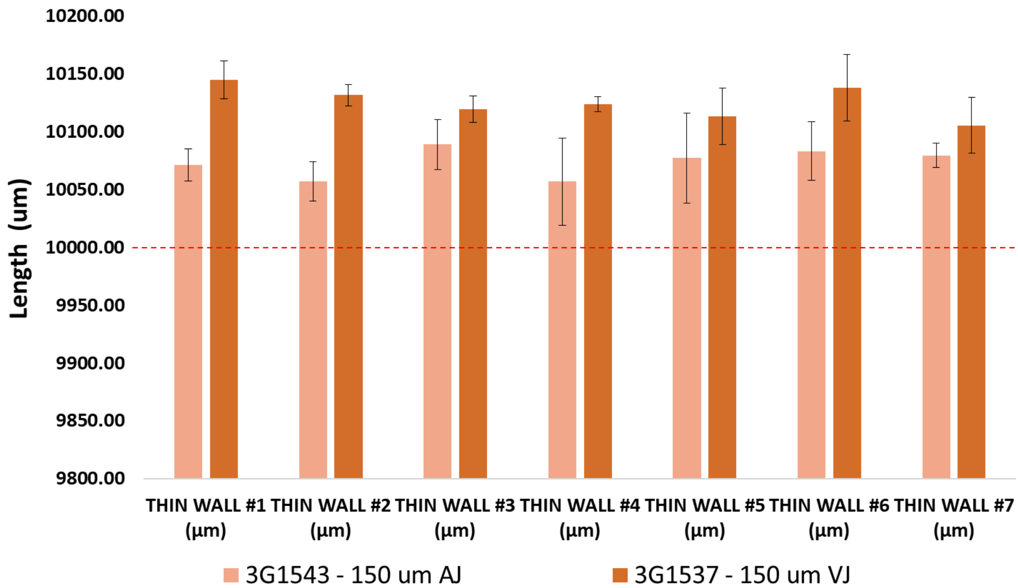


Figure 8. Length measurements across thin walls.

Future Work

This is an ongoing research study in collaboration with GE Research, in which future research will focus on developing correlations between porosity, laser misalignment, and resulting geometry. To achieve this, a higher quantity of specimens with different features than the ones presented in this study will be introduced. Additionally, surface roughness analysis will be performed on all of the new specimen variants.

Conclusion

In this study, we investigated the impact of alignment variations on porosity and geometry in M-LPBF samples. Our findings revealed that the jailhouse variant with angled build direction and gap misalignment resulted in the highest porosity (0.236%), and other variants had insignificant differences in porosity. While correlations between vertical and angled build directions were inconclusive, further exploration across misaligned variants could provide valuable insights. Additionally, geometry measurements highlighted differences in thin wall thickness within and outside stitch regions. Understanding these effects is crucial for optimizing LPBF processes and advancing additive manufacturing reliability. Future research should focus on validating trends across different misalignment scenarios and exploring mitigation strategies for porosity reduction.

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