

**FEDERAL INSTITUTE OF EDUCATION, SCIENCE AND TECHNOLOGY OF  
SANTA CATARINA - CAMPUS FLORIANÓPOLIS  
ACADEMIC DEPARTMENT OF METAL MECHANICS  
BACHELOR'S DEGREE PROGRAM IN MECHATRONICS ENGINEERING**

**MIKAEL BUENO DA SILVEIRA**

**IMPROVEMENT AND CHARACTERIZATION OF ADDITIVELY  
MANUFACTURED EHLA3D SURFACE PROPERTIES**

**AACHEN, 2024.**

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# IMPROVEMENT AND CHARACTERIZATION OF ADDITIVELY MANUFACTURED EHLA3D SURFACE PROPERTIES

**MIKAEL BUENO DA SILVEIRA**

This work has been judged suitable for obtaining the Bachelor's degree in Mechatronic Engineering and approved in its final form by the evaluation committee of the Mechatronic Engineering Course at the Federal Institute of Education, Science and Technology of Santa Catarina.

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## ABSTRACT

In response to the industrial demand for sustainable manufacturing solutions and technologies capable of producing and repairing high-complexity, cost-effective, and high-performance components, Additive Manufacturing (AM) emerges as a viable method for a wide range of materials susceptible to welding, including iron, nickel, titanium, and aluminum-based alloys. Among the array of AM processes, the Extreme High-Speed Laser Material Deposition 3D (EHLA3D) process distinguishes itself as a variant of Laser Metal Deposition (LMD). This method offers notable advantages, such as the capacity to fabricate intricate 3D parts by depositing metal at exceptionally high speeds, in thin layers, and incorporating combinations of materials with low weldability or distinct melting points. Moreover, it results in a smaller thermally affected zone compared to conventional LMD, and due to its proximity to the final geometry (near-net-shape), it entails fewer operations to achieve a part whose geometric shape approaches the desired final design. Nevertheless, the EHLA3D process yields final parts with inherent surface roughness attributed to the process conditions. Melted metal powder particles are projected onto the surface, adhering and generating characteristic process roughness. The current study investigates laser remelting as a post-processing step to refine surface finish, concentrating on the roughness and waviness of surfaces with two primary characteristics: narrow wall side surfaces with rougher finishes and flat tops representing the upper part of a component with roughness and waviness due to the clustering of multiple adjacent weld beads. Various parameters for remelting were considered, including beam diameter (1 mm, 2 mm, and 3 mm), feed rate (2 m/min, 5 m/min, 10 m/min, 20 m/min, and 30 m/min), overlap distance (30%, 50%, and 80%), and laser power (ranging from 200 W to 2700 W). Measurements using a White Light Interferometer (WIM) were conducted both before and after the remelting process to compare initial and final roughness and waviness values. **The study demonstrates that improvements of up to 95.08% in narrow wall side surfaces and up to 76.6% in flat top surfaces are achievable.** While waviness reduction on wall surfaces reached 72.24%, waviness on flat tops showed no significant improvement, remaining stable throughout the process.

**Key words:** Additive Manufacturing, Extreme High-Speed Laser Material Deposition (EHLA3D), Laser Metal Deposition (LMD), Remelting, Surface finish, Roughness, Waviness.

## FIGURES LIST

|                                                                                                                                                                                                                          |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1 - (A) Schematic diagram of the LMD process using a 4-feed jet nozzle (B) LMD process during additive manufacturing of a cylinder.....                                                                           | 20 |
| Figure 2 - Comparison of the process set-ups A) Conventional LMD B) EHLA.....                                                                                                                                            | 22 |
| Figure 3 - Remelting process demonstration.....                                                                                                                                                                          | 24 |
| Figure 4 - WIM Principle.....                                                                                                                                                                                            | 26 |
| Figure 5 - Representation of average depth of roughness parameter (Ra), where the upper line is the Ra parameter value and the dashed line is the CLA.....                                                               | 28 |
| Figure 6 - Representation of average depth of roughness parameter (Rz).....                                                                                                                                              | 28 |
| Figure 7 - Surface texture consists of roughness (left), but also waviness (center) and form error (right).....                                                                                                          | 29 |
| Figure 8 - Separating surface texture (top) into longer-wavelength waviness (middle) and shorter-wavelength roughness (bottom).....                                                                                      | 30 |
| Figure 9 - Development of the deposition and remelting process.....                                                                                                                                                      | 31 |
| Figure 10 - Makino Slim3n machine.....                                                                                                                                                                                   | 33 |
| Figure 11 - Optical system installed in the CNC machine.....                                                                                                                                                             | 34 |
| Figure 12 - Laser power supply LDF 4000-8.....                                                                                                                                                                           | 35 |
| Figure 13 - Powder feeder Twin 150-LC.....                                                                                                                                                                               | 36 |
| Figure 14 - Bead deposition on substrate and cross-section cuts representation.....                                                                                                                                      | 38 |
| Figure 15 - Single layer deposition of parameters set 1, 2, and 3 and cross-section .....                                                                                                                                | 39 |
| Figure 16 - Walls probes deposited with parameter set 3 A) Front of the wall B) Zoom on the deposition defect.....                                                                                                       | 41 |
| Figure 17 - Walls probes deposited with parameter set 3 after cutting the wall apart from the substrate A) Front of the wall showing the deposition defects B) Back of the wall showing very few deposition defects..... | 42 |
| Figure 18 - Top view of the walls deposition 1) Wall deposited with extra beads along the long edges 2) Wall deposition without extra beads along the long edges.....                                                    | 43 |
| Figure 19 - Flat top deposition.....                                                                                                                                                                                     | 44 |
| Figure 20 - Linear hatch deposition path along the x-axis.....                                                                                                                                                           | 45 |
| Figure 21 - 90° cross hatch deposition path.....                                                                                                                                                                         | 46 |
| Figure 22 - Linear hatching deposition with 1 extra welding bead in every layer.....                                                                                                                                     | 47 |
| Figure 23 - Wall used in the DOE parameter exploration with 36 testing fields.....                                                                                                                                       | 50 |
| Figure 24 - Wall with remelted testing fields from stage 3 of the DOE.....                                                                                                                                               | 51 |
| Figure 25 - Sandblasted Wall with Remelting testing fields.....                                                                                                                                                          | 51 |
| Figure 26 - Nexview NX2 by Zygo machine.....                                                                                                                                                                             | 52 |
| Figure 27 - MX setup software Interface.....                                                                                                                                                                             | 53 |

|                                                                                                                                                                                                                                                                                                                                                    |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 28 - Cross-section cut A of bead deposition where A) Deposition height, length and dilution height of p1 B) Deposition area and dilution area of p1 C) Deposition height and dilution height of p2 D) Deposition area and dilution area p2 E) Deposition height, length and dilution height p3 F) Deposition area and dilution area p3..... | 55 |
| Figure 29 - Cross-sections microscope images of parameters set 1, 2, and 3..                                                                                                                                                                                                                                                                       | 57 |
| Figure 30 - EHLA3D block parameter set 1.....                                                                                                                                                                                                                                                                                                      | 58 |
| Figure 31 - EHLA3D block parameter set 2.....                                                                                                                                                                                                                                                                                                      | 58 |
| Figure 32 - EHLA3D block parameter set 3.....                                                                                                                                                                                                                                                                                                      | 59 |
| Figure 33 - A) Top view of the 90° cross-hatching wall deposition. B) Side view of the 90° cross-hatching wall deposition.....                                                                                                                                                                                                                     | 60 |
| Figure 34 - Wall constructed with one extra welding bead at every layer strategy A) Front side B) Back side.....                                                                                                                                                                                                                                   | 61 |
| Figure 35 - Flat Top Deposition.....                                                                                                                                                                                                                                                                                                               | 62 |
| Figure 36 - Result image from the WIM measurement demonstrating a deposition defect that caused increased waviness where A) 3D image and B) 2D image.....                                                                                                                                                                                          | 63 |
| Figure 37 - Result Image of the WIM Measure for Sa and Wa where: A) Reference Wall B) Wa Reference Wall C) Sa Wall remelting test field number 10 D) Wa Wall remelting test field number 10.....                                                                                                                                                   | 63 |
| Figure 38 - Flat top with 36 remelted testing fields.....                                                                                                                                                                                                                                                                                          | 65 |
| Figure 39 - Reflection of a Coin demonstrating shininess obtained after the remelting.....                                                                                                                                                                                                                                                         | 65 |
| Figure 40 - Result image of the WIM measurement for Sa and Wa where: A) Sa Reference flat top B) Wa Reference flat top C) Sa flat top remelting test field number 28 D) Wa flat top remelting test field number 28.....                                                                                                                            | 66 |
| Figure 41 - 1, 2, 3 mm beam Comparison at 2 m/min and 80% overlap hatch distance applied on walls without deposition defects where laser power of 500, 1700 and 1700 W were applied respectively.....                                                                                                                                              | 67 |
| Figure 42 - Power variation at 2 m/min, 80% overlap hatch and 2 mm beam diameter applied on walls without deposition defects.....                                                                                                                                                                                                                  | 68 |
| Figure 43 - Power variation at 2 m/min, 80% overlap hatch and 3 mm beam diameter applied on walls without deposition defects.....                                                                                                                                                                                                                  | 68 |
| Figure 44 - 1, 2, 3 mm beam Comparison at 2 m/min and 80% overlap hatch distance applied on walls with deposition defects where laser power of 500, 1700 and 1700 W were applied respectively.....                                                                                                                                                 | 69 |
| Figure 45 - Power variation at 2 m/min, 80% overlap hatch, and 2 mm beam diameter applied on walls with deposition defects.....                                                                                                                                                                                                                    | 70 |
| Figure 46 - Power variation at 2 m/min, 80% overlap hatch and 3 mm beam diameter applied on walls with deposition defects.....                                                                                                                                                                                                                     | 70 |
| Figure 47 - 1 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops.....                                                                                                                                                                                                                        | 71 |
| Figure 48 - 2 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops.....                                                                                                                                                                                                                        | 71 |

|                                                                                                                                                                                           |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 49 - 3 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops.....                                                               | 72 |
| Figure 50 - 1, 2, 3 mm beam comparison at 30 m/min and 80% overlap hatch applied on flat top surfaces where laser power of 1300, 1800 and 2300 W were applied respectively.....           | 72 |
| Figure 51 - 2 m/min at 80% overlap hatch, 2 mm beam diameter, and laser power variation applied on walls without deposition defects.....                                                  | 73 |
| Figure 52 - 5 m/min at 80% overlap hatch, 2 mm beam diameter, and laser power variation applied on walls without deposition defects.....                                                  | 74 |
| Figure 53 - 2 m/min at 80% overlap hatch, 2 mm beam diameter and laser power variation applied on walls with deposition defects.....                                                      | 74 |
| Figure 54 - 5 m/min at 80% overlap hatch, 2 mm beam diameter and laser power variation applied on walls with deposition defects.....                                                      | 75 |
| Figure 55 - Feed rate variation applied on the flat top at 80% overlap hatch and 1 mm beam diameter where laser power of 500, 300, 800, 1100 and 1300 W were applied respectively.....    | 76 |
| Figure 56 - Feed rate variation applied on the flat top at 80% overlap hatch and 2 mm beam diameter where laser power of 700, 1000, 1600, 2100 and 1800 W were applied respectively.....  | 76 |
| Figure 57 - Feed rate variation applied on the flat top at 80% overlap hatch and 3 mm beam diameter where laser power of 1100, 1300, 1500, 1800 and 2300 W were applied respectively..... | 76 |
| Figure 58 - 50% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power. ....                                    | 77 |
| Figure 59 - 80% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power. ....                                    | 78 |
| Figure 60 - 50% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls with deposition defects while varying laser power..                                           | 79 |
| Figure 61 - 80% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power. ....                                    | 79 |
| Figure 62 - 50% overlap hatch comparison at 5 m/min and 1 mm beam diameter applied on flat top deposition while varying laser power.....                                                  | 80 |
| Figure 63 - 80% overlap hatch comparison at 5 m/min and 1 mm beam diameter applied on flat top deposition while varying laser power.....                                                  | 80 |
| Figure 64 - Results of Sa and Wa values from the sandblasted wall at a feed rate of 2 m/min, beams diameter of 2 mm and 80% overlap hatch while varying laser power.....                  | 81 |
| Figure 65 - Results of Sa and Wa values from the non-sandblasted wall at a feed rate of 2 m/min, beams diameter of 2 mm and 80% overlap hatch while varying laser power.....              | 82 |
| Figure 66 - Comparison between initial and final Sa values for walls without                                                                                                              |    |



deposition defects, walls with deposition defects, and flat top depositions.....83  
Figure 67 - Comparison between initial and final  $Wa$  values for walls without  
deposition defects, walls with deposition defects, and flat top depositions.....83

## TABLES LIST

|                                                                                                                       |    |
|-----------------------------------------------------------------------------------------------------------------------|----|
| Table 1 - Parameters set 1, 2 and 3 used on the beads deposition study.....                                           | 38 |
| Table 2 - Hatch distance used in each parameter set.....                                                              | 39 |
| Table 3 - Parameters set 1, 2 and 3 laser power variation for blocks deposition...                                    | 40 |
| Table 4 - Parameter variation range.....                                                                              | 41 |
| Table 5 - Wall dimensions.....                                                                                        | 41 |
| Table 6 - Flat top dimensions.....                                                                                    | 43 |
| Table 7 - Remelting parameters.....                                                                                   | 48 |
| Table 8 - Qualitative evaluation of parameters observed during the remelting process.....                             | 48 |
| Table 9 - Parameters settings used for WIM measurements.....                                                          | 53 |
| Table 10 - Filters applied after the WIM measurements.....                                                            | 54 |
| Table 11 - Bead Measurements of parameter set 1, 2 and 3.....                                                         | 55 |
| Table 12 - Block measurements for parameter sets 1, 2 and 3.....                                                      | 59 |
| Table 13 - Reference measurement results for roughness and waviness.....                                              | 64 |
| Table 14 - Remelting parameters used in the comparison between reference and best results achieved for Sa and Wa..... | 84 |

## **ABBREVIATIONS AND ACRONYMS LIST**

|                    |                                                              |
|--------------------|--------------------------------------------------------------|
| 3D                 | Three Dimensional                                            |
| AM                 | Additive Manufacturing                                       |
| CAD                | Computer-Aided Design                                        |
| CNC                | Computer Numerical Control                                   |
| dcore              | Fiber Core Diameter                                          |
| DED                | Direct Energy Deposition                                     |
| df                 | Focus Diameter                                               |
| EHLA3D             | Extreme High-Speed Laser Material Deposition in 3 Dimensions |
| FOV                | Field of view                                                |
| g/min              | Gram per Minute                                              |
| HAZ                | Heat Affected Zone                                           |
| Laser              | Light Amplification by Stimulated Emission of Radiation      |
| LMD                | Laser Metal Deposition                                       |
| LP                 | Laser Polishing                                              |
| LPBF               | Laser Powder Bed Fusion                                      |
| LSS                | Laser Spot Size                                              |
| m/min              | Meter per Minute                                             |
| m/s                | Meter per Second                                             |
| mm                 | Millimeter                                                   |
| mm <sup>2</sup>    | Square Millimeter                                            |
| mm <sup>3</sup> /s | Cubic Millimeter per Second                                  |
| MMC                | Metal Matrix Composites                                      |
| mrاد               | Milliradian                                                  |

|               |                                          |
|---------------|------------------------------------------|
| nm            | Nanometer                                |
| PID           | Proportional–Integral–Derivative         |
| PL            | Laser Power                              |
| PMF           | Powder Mass Flow                         |
| RZ            | Average Roughness of a Measurement Trace |
| Sa            | Average Roughness of a Surface Area      |
| SLM           | Selective Laser Melting                  |
| SLS           | Selective Laser Sintering                |
| Wa            | Average Waviness of a Surface Area       |
| WIM           | White Light Interferometer               |
| $\lambda$     | Lambda                                   |
| $\mu\text{m}$ | Micrometer                               |
| %             | Percent                                  |

## TABLE OF CONTENTS

|                                                                  |           |
|------------------------------------------------------------------|-----------|
| <b>1 INTRODUCTION.....</b>                                       | <b>14</b> |
| <b>1.1 Justification.....</b>                                    | <b>15</b> |
| <b>1.2 Problem Definition.....</b>                               | <b>16</b> |
| <b>1.3 Objective.....</b>                                        | <b>16</b> |
| <b>1.4 Specific Objectives.....</b>                              | <b>16</b> |
| <b>2 STATE OF THE ART.....</b>                                   | <b>18</b> |
| <b>2.1 Additive Manufacturing.....</b>                           | <b>18</b> |
| 2.1.1 Laser Material Deposition.....                             | 19        |
| 2.1.2 Laser Powder Bed Fusion.....                               | 21        |
| 2.1.3 EHLA.....                                                  | 21        |
| 2.1.4 EHLA3D.....                                                | 22        |
| <b>2.2 Post Processing.....</b>                                  | <b>23</b> |
| 2.2.1 Laser Polishing.....                                       | 23        |
| <b>2.3 Characterization Methods of Surface Properties.....</b>   | <b>25</b> |
| 2.3.1 White Light Interferometer.....                            | 25        |
| 2.3.1.1 Filters.....                                             | 26        |
| 2.3.1.2 Roughness.....                                           | 27        |
| 2.3.1.3 Waviness.....                                            | 29        |
| <b>3 METHODOLOGY.....</b>                                        | <b>31</b> |
| <b>3.1 Material.....</b>                                         | <b>31</b> |
| <b>3.2 Deposition Setup.....</b>                                 | <b>32</b> |
| 3.2.1 Experimental Set-Up.....                                   | 32        |
| <b>3.3 Deposition Process.....</b>                               | <b>36</b> |
| 3.3.1 Parameters Definition.....                                 | 36        |
| 3.3.2 Geometry Definition.....                                   | 41        |
| 3.3.3 Deposition Strategy.....                                   | 44        |
| 3.3.3.1 Linear Hatching Deposition.....                          | 45        |
| 3.3.3.2 90° Cross-hatching Deposition.....                       | 45        |
| 3.3.3.3 Linear Hatching Deposition with Extra Welding Beads..... | 46        |
| <b>3.5 Analysis Methodology.....</b>                             | <b>52</b> |
| <b>4 RESULTS.....</b>                                            | <b>55</b> |
| <b>4.1 Beads Deposition.....</b>                                 | <b>55</b> |
| <b>4.2 Single Layers Deposition Study.....</b>                   | <b>56</b> |
| <b>4.3 Block Deposition Study.....</b>                           | <b>57</b> |
| <b>4.4 90° Cross-hatching Wall Deposition.....</b>               | <b>60</b> |

|                                                                          |           |
|--------------------------------------------------------------------------|-----------|
| <b>4.5 Linear Hatching Wall Deposition with Extra Welding Beads.....</b> | <b>61</b> |
| <b>4.6 Flat Top Deposition.....</b>                                      | <b>62</b> |
| <b>4.7 Reference Roughness and Waviness Measurements.....</b>            | <b>62</b> |
| <b>4.8 Remelting Results.....</b>                                        | <b>64</b> |
| 4.8.1 Laser Beam Diameter Variation.....                                 | 66        |
| 4.8.2 Feed Rate Variation.....                                           | 73        |
| 4.8.3 Hatch Overlap Distance.....                                        | 77        |
| 4.8.4 Sandblasted walls.....                                             | 81        |
| <b>4.9 Remelting Results Overview.....</b>                               | <b>82</b> |
| <b>5 FINAL CONSIDERATIONS.....</b>                                       | <b>85</b> |
| <b>5.1 Suggestions for Future Research.....</b>                          | <b>87</b> |
| <b>REFERENCES.....</b>                                                   | <b>88</b> |

## 1 INTRODUCTION

Over decades, the industry has predominantly relied on subtractive manufacturing. However, according to Hodonou et al. (2019), "Machining of aircraft structural components can waste up to 90% of the raw material. Therefore, evaluation of alternative manufacturing processes for those components is crucial for reducing the economic and environmental impacts of manufacturing." Various metrics are utilized to assess not only the economic performance but also the environmental and societal sustainability performance of a manufacturing line. These include "process water consumption, raw material usage, energy consumption, potential hazards concerning the work environment, and the physical work done by the employees" (Pusateri et al., 2024).

Additive Manufacturing (AM), particularly that conducted with laser technology, emerges as a promising option for the industry. Laser Material Deposition (LMD), widely employed in the manufacturing of three dimensional (3D) parts with complex geometries, prototypes, mold repairs, and coatings, now faces competition from a more viable alternative to meet the growing industry demands: Extreme High-Speed Directed Energy Deposition in Three Dimensions (EHLA3D). It is also utilized in the oil and gas industry for coating tubes and ducts with materials capable of resisting high oxidation levels. "In areas with higher roughness or surface defects, localized corrosion can occur, compromising the strength of equipment or pipelines. To enhance the surface finish, subsequent machining processes are often required after coating" (Teichmann, 2016, p. 49).

EHLA3D is an innovative variant of conventional LMD that redefines the approach of conventional LMD by heating powder particles to their melting temperature, above the substrate surface. This process results in a more efficient deposition of powder particles, generating remarkably higher process speeds. With lower heat input, this technique allows coating highly heat sensitive materials such as aluminum and alloys of iron, nickel, and titanium, opening new possibilities for additive manufacturing.

This deposition technique offers feed rates that can reach up to 300 m/min when applied on rotational parts. It is essential to consider post-processing steps to ensure that the surfaces of manufactured parts meet the rigorous standards of

roughness, waviness, and geometric tolerances established in the design. In this context, laser surface remelting emerges as a promising post-processing strategy, aiming to enhance the surface quality of parts and reduce their irregularities to acceptable levels.

This study proposes a thorough approach in characterizing the top surfaces of cubes and lateral faces of cuboids made of stainless steel 316L, produced through the EHLA3D process. The analysis will investigate into the laser remelting process, aiming to improve surfaces that, due to the characteristics of the EHLA3D process, exhibit some roughness caused by powder particles projected and adhered to surfaces during metal deposition. The roughness generated by the EHLA3D process often does not meet industry requirements, necessitating the development of techniques that maintain the method's efficiency while reducing the effort of post-processing.

## **1.1 Justification**

The significant advancements in AM technologies, including the evolution of laser sources, optical systems, and processes, coupled with the ability to work with high-value metal alloys such as AISI 4340, have enabled industries like aerospace to build, repair, or coat parts through LMD. "If these high-quality components of AISI 4340 material fail, effective repair procedures are an important means of reducing costs and extending the lifespan" (Li, 2019, p. 1).

Given this scenario, conducting this study is justified to explore strategies for enhancing the surface properties of parts manufactured by EHLA3D. The implementation of laser remelting is motivated by investigating the feasibility of improving surface quality and integrating this process with the same machine that deposited the part, thereby reducing process time and consequently production costs.



## **1.2 Problem Definition**

High speed during the deposition process can result in surface imperfections, limiting the suitability of EHLA3D technology in components that require high standards of finishing characterized by low levels of roughness and waviness. To meet the specific geometric tolerances of each component, it becomes imperative to incorporate post-processing steps.

It is important to note that there is a scarcity of studies dedicated to the surface finishing of parts built by EHLA3D, highlighting the significant relevance of this work for the advancement and development of this technology.

## **1.3 Objective**

The main objective is to minimize the need for any post-processing, enabling the attainment of final geometries that meet industrial quality specifications. Focusing on simple geometries such as cubes and narrow cuboids, this study seeks to establish a solid foundation for comprehending and optimizing the remelting process. The results obtained could hold significant practical implications for the efficiency and applicability of this method in manufacturing 3D parts for various industrial applications. In parallel, the effects of laser remelting on these surfaces will be investigated, with an emphasis on minimizing surface properties inherent to the manufacturing process, such as high roughness and unwanted surface waviness.

## **1.4 Specific Objectives**

The specific objectives of this work are as follows:

- a) Deposition of narrow cuboid probes by EHLA3D measuring 120 x 6,75 x 80 mm;
- b) Deposition of flat top measuring 130 x 130 x 6,75 mm;
- c) Identify surface characteristics through topographic analyses;

- d) Apply laser remelting surface post-processing technique on test fields of 17 x 17 mm;
- e) Reevaluation of the remelted surfaces.

## **2 STATE OF THE ART**

Additive manufacturing has been incorporated into industry since the 1980s, with 1986 being the year when 3D Systems, a company founded by Chuck Hull, first introduced AM technology to the commercial market (Leach; Carmignato, 2021, p. 1). Chuck Hull is credited with creating the Stereolithography (SLA) technology, which in turn is an AM technique.

Recognized as an advanced manufacturing method, AM encompasses various deposition techniques, using a variety of machines with distinct characteristics. This approach offers the flexibility to work with different materials, including polymers, ceramics, and metals. This chapter proposes to provide an overview of the laser-based metal AM technologies, with an emphasis on LMD and EHLA3D processes, as well as the techniques currently available for enhancing their surfaces.

### **2.1 Additive Manufacturing**

AM is an advanced manufacturing process based on the layer by layer joining of materials to create physical objects from models designed by Computer Assisted Drawing (CAD) software. According to the ASTM 52900, the AM process is defined as “a method of the joining of materials to fabricate parts from 3D-model data, made layer upon layer. This process is opposed to formative manufacturing and subtractive manufacturing methodologies”.

This results in higher precision, efficiency, and speed in manufacturing processes. “This class of technologies is capable of creating parts with complex shapes and intricate structures.” (Geng; Bidanda, 2021 p. 1). Complex parts, typically assembled from various components, can be built as a single piece, eliminating the need for fasteners. “One of the main advantages of the AM process is the production of complex-structured parts that find application in aerospace, medical industries, etc., because the traditional manufacturing processes for these specific parts are extremely limited.” (Tebianian et al., 2023, p. 1)

At the end of the manufacturing process, some design requirements may necessitate a surface refinement step to reduce roughness and surface waviness, as well as the removal of the base substrate where the first layer of the part was deposited. "One critical issue is the low quality of the AM-created parts." (Geng; Bidanda, 2021 p. 2). This section details some of the most common laser metal deposition processes available today, including the innovative EHLA3D process, which combines conventional LMD deposition with very high feed rates providing high productivity and the processability of difficult to weld material due to lower heat input.

### 2.1.1 Laser Material Deposition

Laser has been widely employed in the construction of complex three-dimensional geometries using various types of materials, such as polymers (Wencke et al., 2020, p. 1), ceramics (Wu et al., 2020, p. 12761), and metal alloys (Cooke et al., 2020, p. 985). One of the main advantages of using lasers in the material fusion process for additive manufacturing lies in the precision with which the size of the laser beam focal point can be adjusted. This precise control has positive effects, mitigating undesirable defects caused by the Heat Affected Zone (HAZ). In this area, the material, although not melted, may have undergone phase transformations in the solid state, recrystallization, and/or grain growth (Santos, 2001, p. 7). Additionally, advancements in the development of advanced control systems, specifically tailored to laser sources and optical systems, enable the achievement of a more stable process. This refined control allows for the regulation of the amount of energy deposited in the part during processes that use the laser as an energy source, such as LMD and EHLA3D.

The laser can be focused and shaped with specific energy distribution, travel according to path strategy planning, and melt material in powder form, enabling the fabrication of 3D components or the repair of damaged or worn parts. "The use of the LMD process in repairing high-value parts that could not be repaired in the past or were difficult to repair was made possible by the lower thermal damage associated

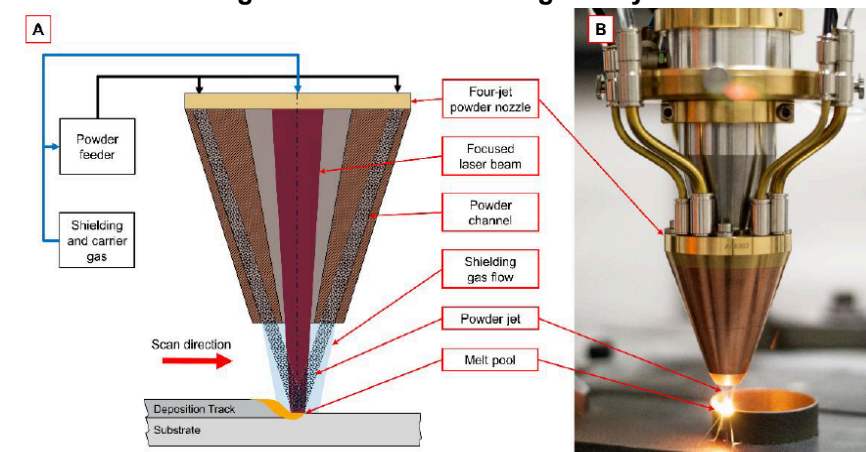
with the process through a well-controlled heat-affected zone" (Mahamood, 2018, p. 4).

LMD processes enable the construction of large components, component repair, and the application of corrosion and wear protection layers. "DED (Direct Energy Deposition) can be used to effectively repair and rehabilitate defective and damaged high-tech components in service, such as turbine blades" (Gibson, Rosen and Stucker, 2015, p. 266).

The LMD system consists of an injector nozzle that directs the material in a coaxial manner relative to the laser beam. An inert gas is responsible for transporting the material from the powder feeder to the nozzle, and in addition to the carrier gas, an inert shielding gas is delivered through the center of the nozzle toward the workpiece.

The laser beam coincides with the focus of the metallic powder and then heats the deposited material to its melting point, causing it to melt and fuse with the surface of the substrate in the form of welding beads. As the laser melts the deposited material, the laser beam is moved across the substrate surface according to the desired strategy path plan. This process is repeated layer by layer, with each subsequent layer fusing onto the previous one, gradually building up the desired 3D component. Figure 1 shows a representation of an LMD system and a real image of a nozzle used for LMD.

**Figure 1 - (A) Schematic diagram of the LMD process using a 4-feed jet nozzle (B) LMD process during additive manufacturing of a cylinder**



Source: Schmidt (2021 p. 3).

### 2.1.2 Laser Powder Bed Fusion

The LPBF method was patented by Fraunhofer ILT (Institut für Lasertechnik) in 1997 and is also known by the name Selective Laser Sintering (SLS) or Selective Laser Melting (SLM). "LS/LM/LMD, capable of processing a wide range of metals, alloys, ceramics, and Metal Matrix Composites (MMCs), are currently considered the most versatile AM techniques" (Gu, 2015, p. 8). The main characteristic of the LPBF process is that a small focal point can be used for rapid scanning of areas through galvanic mirrors. "The powder bed fusion process is used to produce objects from powder materials using one or more lasers to selectively fuse or melt the particles on the surface, layer by layer, in an enclosed chamber" (ISO/ASTM 52900, 2021, 3.8.10).

Geometric accuracies achieved by LPBF are superior compared to LMD processes, highlighting a comparison between LMD and LPBF processes. Among the data provided, LPBF stands out for its low levels of roughness, whereas LMD is notable for its high deposition rate.

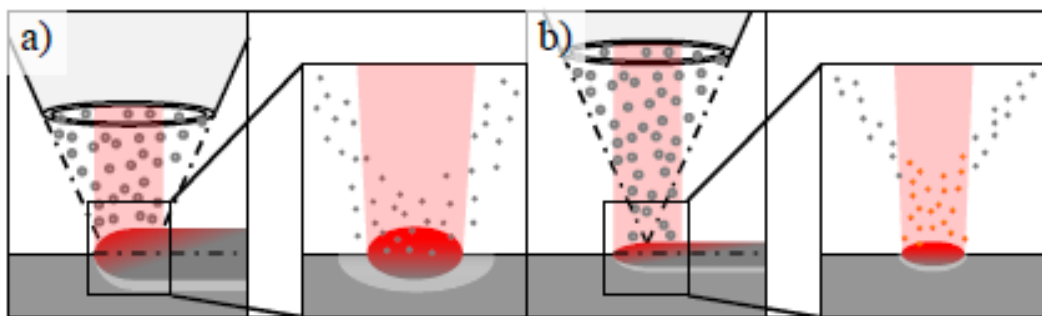
### 2.1.3 EHLA

EHLA is an innovative modification of the traditional LMD method widely employed across various sectors of the industry for coating cylindrical parts. It is capable of achieving high productivity in coating applications due to its higher feed rates compared to LMD, meeting the industry's demand for higher process speeds (Brucki et al., 2023).

Derived from the German acronym for high-speed laser material deposition, EHLA is characterized by elevated process speeds of up to 200 m/min, increased cooling rates, and a significantly reduced heat affected zone (Li et al., 2019), which result in smaller weld bead deposition and thinner layer thicknesses compared to conventional LMD (Ko, Zhang and Schopphoven, 2023, p. 1). The processing of material combinations with poor weldability or different melting points is possible, with simultaneously smaller heat-affected zone and dilution zone compared to conventional LMD, as lower heat input is absorbed by the part (Schaible et al., 2020, p. 1).

The key feature of EHLA that enables the process to achieve such high feed rates is that the focus of the powder gas jet is positioned above the melt pool so that the powder particles are melting above the processing surface by absorbing most of the beam power in flight (Ko, Zhang and Schopphoven, 2023, p. 1) (see figure 2). Liquid particles hit the surface, creating a layer, and higher speeds are feasible because there is no need to wait for the melting of the particles in a melt pool.

**Figure 2 - Comparison of the process set-ups A) Conventional LMD B) EHLA**



Source: Ko, Zhang and Schopphoven (2023, p1).

One limitation of the EHLA process is the capability to process only rotational symmetric components like cylinders, shafts and disks. This limitation results from the machine types, which are modified lathes (Ko, Zhang and Schopphoven and 2023, p. 1), where lateral movements are not possible.

#### 2.1.4 EHLA3D

Considering the limitation of EHLA, where lateral movements are not possible, LMD based volume deposition requires a handling system that allows precise movement and has a high repeat accuracy, as well as a movement in at least three axes (Schaible et al., 2020, p. 1). However, standard milling machines cannot operate with high feed rates.

EHLA for additive manufacturing (AM) aims at manufacturing highly individualized parts with high volume buildup rates and finer structural resolution compared to conventional LMD. The main steps toward harnessing EHLA for AM, termed EHLA3D, are (a) process parameter development for volume buildup through deposition of multiple layers on top of each other and (b) the development of system technology that allows

relative spatial movement between the powder nozzle and the substrate at high speeds and high accuracy in three dimensions. With a fast back-and-forth motion, high acceleration rates are necessary to ensure high volume buildup rates and high powder deposition efficiency. (Schaible et al., 2020, p. 1).

At the end of the last decade, studies conducted at ILT led to the concept of applying the EHLA process to a five-axis Computer Numerical Control (CNC) machine, equipped with optical systems powered by a high-power laser source and capable of reaching feed rate of up to 30 m/min. Peripherals such as a pneumatic powder feeder, cooling systems for the optical system and nozzle, and an exhaust system were adapted as essential components for the EHLA3D deposition process.

## **2.2 Post Processing**

Most AM processes require post-processing after their construction to prepare the part for its intended use, shape, or function. In the current global market, companies capable of efficiently delivering a part with good surface finishes along with the accuracy that meets their client's design have the opportunity to charge a differentiated value for their services (Gibson, Rose and Stucker, 2015, p. 329). Most post-processing methods are applied to support material removal, improvement in surface roughness, accuracy enhancements, and aesthetics.

After the AM process, many parts need to undergo post-processing steps to achieve the appropriate surface texture for each component's design and geometric accuracy. "The surface quality of AM parts is commonly lower because of the layer by layer processing and the staircase effect." (Peng et al., 2021, p. 2). In the case of metals, this step can be even more relevant, as heat treatments applied as a post-processing step can improve metallurgical and microstructural characteristics and result in the reduction of residual stresses in the part.

### **2.2.1 Laser Polishing**

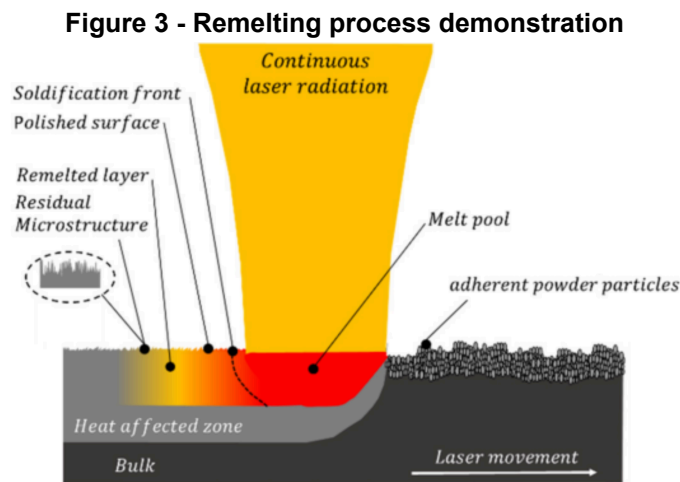
Laser polishing is a sophisticated surface finishing technique characterized by the controlled remelting of a thin layer through fusion and solidification, distinguishing it from conventional methods reliant on mechanical or chemical forces. This process



is based on the principle of melting and resolidification of a thin surface layer of material, achieved by directing a high-intensity laser beam onto the workpiece surface (Gisario, Barletta, Veniali, 2022, p. 5).

AM processes often yield parts with poor surface quality, geometric tolerances, and microstructural characteristics, impacting the overall quality of the produced components. The inferior surface roughness associated with additively manufactured parts can adversely affect both surface integrity and geometric tolerances (Ali et al., 2023, p. 1). However, numerous studies have demonstrated substantial enhancements in the surface roughness of additively manufactured metal parts through laser polishing, making it a useful technique in refining various ferrous and non-ferrous parts over the past two decades (Cvijanovic, Bordatchev, Tutunea-Fatan, 2023, p. 1).

In laser polishing, the application of a laser beam brings a superficial layer of initial surface topography (peaks and valleys) to a molten state, facilitating the smoothing process (Cvijanovic, Bordatchev and Tutunea-Fatan, 2023, p. 1). Figure 3 presents a demonstration of the remelting process.



Source: Hofele et al. (2021).

This technique offers many advantages, including precision, efficiency, and environmental friendliness, when compared to traditional polishing methods. It is distinguished by its contactless nature, high accuracy, and flexibility, with the capability of being fully automated (Primus et al., 2022, p. 2).

## 2.3 Characterization Methods of Surface Properties

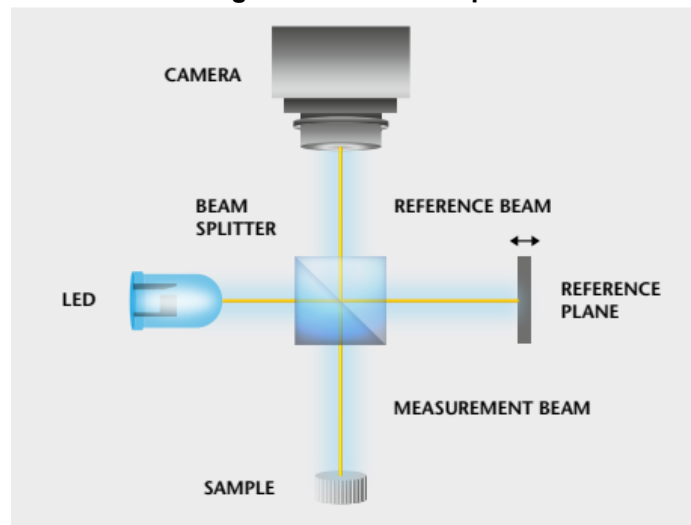
This section provides an overview of measurement methods, focusing on White Light Interferometry (WIM) for surface analysis. It introduces parameters analysis such as filters and surface roughness and waviness, highlighting their importance in characterizing surface properties with precision.

### 2.3.1 White Light Interferometer

White light interferometry is an optical technique used for precise surface profiling of samples in scientific research and industrial applications. This method employs white light, or broadband light, to measure surface characteristics with high precision. The principle behind WIM involves scanning the temporal coherence function of the broadband light reflected from the sample under test (Hýbl, Berger, Häusler, 2008, p. 1). The key component of a white light interferometer is its ability to analyze interference patterns generated by the interaction of light waves reflected from the sample surface and a reference mirror.

The measured object replaces one of the interferometer's mirrors. The other mirror is used as the reference mirror. The position of the reference mirror defines the reference plane in the object arm. The distance of the reference plane from the beam splitter is the same as the distance of the reference mirror from the beam splitter. The reference plane is depicted by the dashed line in Fig. 1. A telecentric telescope is used as the imaging system. (Pavliček, Mikeska, 2019, p.1).

By analyzing these interference patterns, a white light interferometer provides detailed insights into surface roughness, texture, and topography with nanometer-scale resolution. Features of varying heights on the object surface produce distinct phase patterns mixed with light from the reference, enabling precise measurement of surface characteristics (Bauer, Werber, Chanbai, 2013). Figure 4 presents the WIM principle.

**Figure 4 - WIM Principle**

Source: Polytec GmbH (2021, p. 5).

Overall, white light interferometry stands as a powerful tool for surface metrology, facilitating advancements in scientific research and industrial quality control processes.

#### 2.3.1.1 Filters

Short and long period filters are used in surface metrology, particularly to analyze roughness and waviness measurements. These filters are instrumental in distinguishing different surface features, leading to a more accurate assessment of surface characteristics.

At present, filtering technology is the main method used to separate surface roughness and other low frequency components. It can decompose the measured surface topography signal in the frequency domain, yielding different components. The wavelength components are separated into well-defined bandwidths without having to represent the surface topography as a specific function. (He et al., 2021, p. 1).

Short period filters remove high frequency noise and isolate roughness components, while long period filters separate low frequency variations and identify waviness features. “The low frequency, intermediate frequency and high frequency components in the signal correspond to the macroscopic form error, surface waviness, and surface roughness, respectively. (He et al., 2021, p. 1).

One commonly used filter is the Gaussian filter, which applies a Gaussian weighting function to the measured data. This filter effectively separates the surface

profile into roughness and waviness components by smoothing out high frequency noise while preserving low frequency features.

Another important filter is the bandpass filter, which selectively allows a specific range of spatial frequencies to pass through. By isolating either the roughness or waviness components of the surface profile, the bandpass filter helps to enhance clarity and accuracy in surface characterization.

The low pass filter is employed to attenuate high frequency components of the surface profile, isolating the low frequency waviness component. This filter is particularly useful for analyzing surfaces with prominent waviness features, providing insights into their characteristics.

Conversely, the high pass filter attenuates low frequency components, isolating the high frequency roughness component. This filter is effective for detecting fine surface irregularities and micro features that contribute to surface roughness.

#### 2.3.1.2 *Roughness*

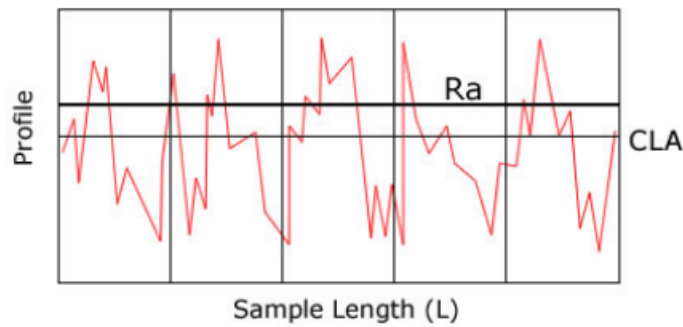
Roughness in additive manufacturing can be influenced by various factors including the layer by layer deposition process, material properties, printing parameters, and post-processing techniques. “Surface roughness is a micro geometric irregularity of the surface, which occurs during the processing of a particular surface or other influences.” (Mahovic Poljaček et al., 2021, p. 4).

The DIN 4768 standard provides guidelines for the measurement and evaluation of surface roughness parameters in industrial applications. It specifies methods for determining parameters such as  $Ra$  (average roughness),  $Rz$  (maximum height of the profile),  $Rq$  (root mean square roughness). “The Arithmetic Mean Roughness parameter ( $Ra$ ) specifies the arithmetic mean of the absolute amounts of all variances in the roughness profile from the center line over the total distance, and it is represented by the equation 1.” (Amaral et al., 2009, p. 2)

$$Ra = \frac{1}{L} \int_0^L |y(x)| dx \quad (1)$$

Where  $L$  is the total sampling length and  $y$  is the surface profile height to the Center Line Average (CLA), and it is a function of position. (Amaral et al., 2009, p. 2). Figure 5 presents a schematic representation of  $Ra$  definition.

**Figure 5 - Representation of average depth of roughness parameter ( $Ra$ ), where the upper line is the  $Ra$  parameter value and the dashed line is the CLA**

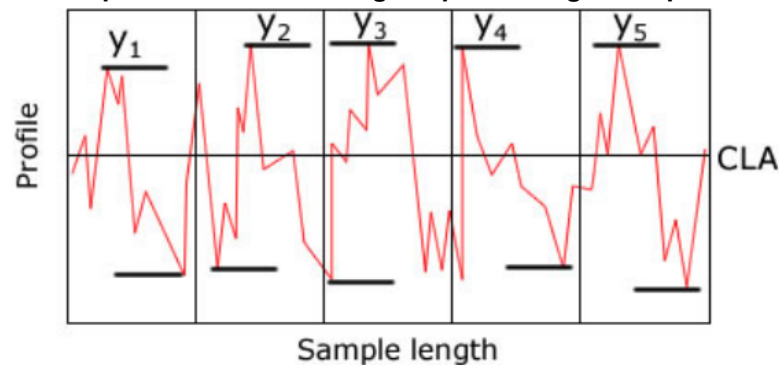


Source: Amaral et al., (2009, p. 2).

The Average Depth of Roughness ( $Rz$ ) is the arithmetic mean of the distance between global maximum and minimum ( $Y_i$ ) in five successive single measuring sections of the total evaluation length. (Amaral et al., 2009, p. 2). Equation 2 represents the  $Rz$  measurement. Figure 6 presents a schematic representation of the average depth of roughness parameter ( $Rz$ ).

$$Rz = \frac{1}{5} \sum_{i=1}^5 y_i \quad (2)$$

**Figure 6 - Representation of average depth of roughness parameter ( $Rz$ )**

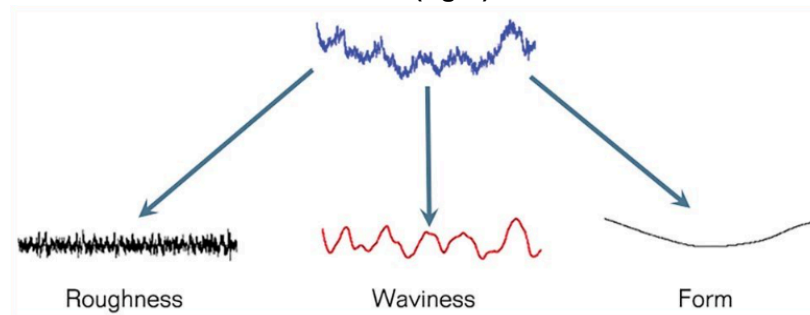


Source: Amaral et al., (2009, p. 2).

### 2.3.1.3 Waviness

Waviness  $W_a$  is referred to as the Arithmetic Mean Waviness for the profile (Keyence, 2024). According to Stahli (2013), The waviness (also known as peaks and valleys) is a calculation of surface irregularities with a spacing greater than the surface roughness.  $W_a$  measurement is a similar process to filtering roughness, however, waviness typically refers to the larger scale variations in the surface profile, representing features such as waviness and form errors. Figure 7 presents a surface texture composition.

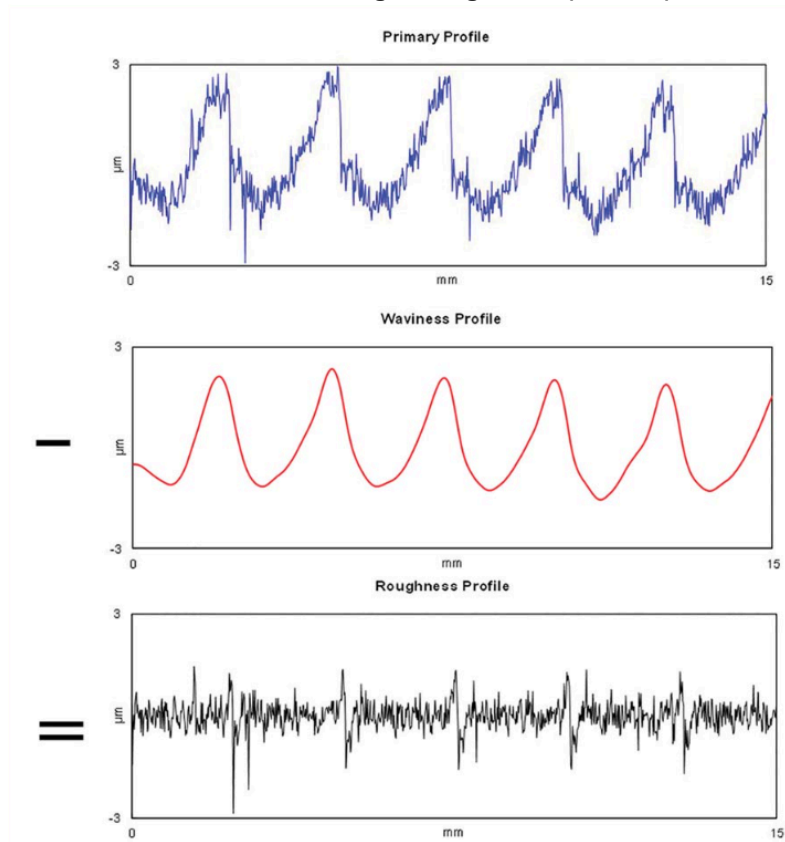
**Figure 7 - Surface texture consists of roughness (left), but also waviness (center) and form error (right)**



Source: Zecchino and Malburg (2023).

Figure 8 presents a profile surface measurement where the roughness and waviness are isolated from the original profile after a filtering application process.

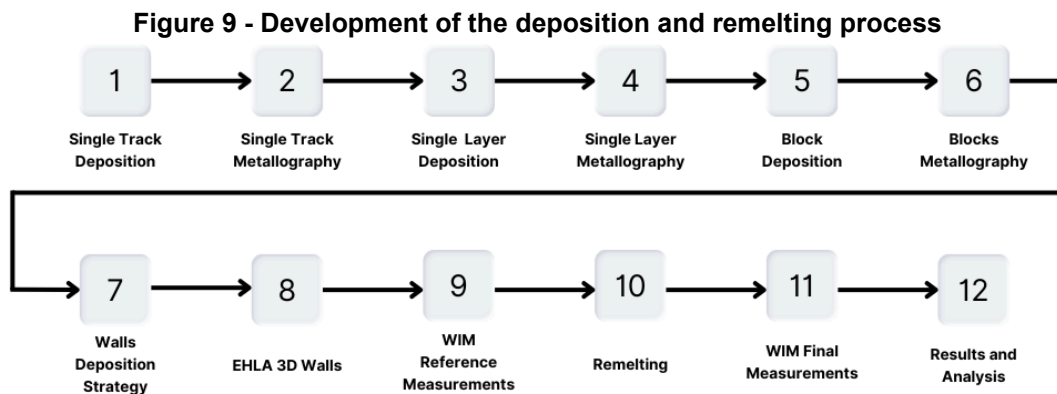
**Figure 8 - Separating surface texture (top) into longer-wavelength waviness (middle) and shorter-wavelength roughness (bottom)**



Source: Zecchino and Malburg (2023).

### 3 METHODOLOGY

In this chapter, the configuration and materials utilized for conducting the EHLA3D deposition and laser remelting process are outlined. The equipment employed, machine specifications, deposition parameters, surface measurement techniques, and specifics regarding the laser utilized in the experiments are described. A flow chart illustrating the development of the deposition and remelting process is shown in figure 9.



Source: Own authorship.

#### 3.1 Material

The selection of the chemical composition of materials is made to meet the desired mechanical characteristics. AM performed through laser deposition offers the flexibility to use a variety of materials. Because of favorable mechanical properties, excellent corrosion and processability, 316L stainless steels are of great importance in aerospace, marine, gas and chemical industries (Li et al., 2023, p. 1). Stainless steel 316L is an austenitic alloy distinguished by its lower carbon content compared to 316. With chromium content between 16% and 18%, nickel between 10% and 14%, and 2% to 3% molybdenum, along with trace amounts of manganese, phosphorus, silicon, and sulfur, this composition minimizes the risk of intergranular corrosion.

In this study, both the substrate and the metallic powder used as the additive material are stainless steel 316L. The substrate plates originally measured



150 x 150 x 10 mm, covering a total area of 22500 mm<sup>2</sup>. Substrates used for the flat-top depositions are used as original measurements and substrates used for the wall depositions have the dimension of 150 x 30 x 10 mm with a total area of 4500 mm<sup>2</sup>. The metallic powder, supplied by Makino, consists of spherical particles ranging in size from 15 µm to 45 µm.

### **3.2 Deposition Setup**

This section will describe the experimental set-up used for the EHLA3D deposition, parameters used, deposition strategies and remelting procedures.

#### **3.2.1 Experimental Set-Up**

The CNC machine employed in the deposition process is a prototype machining center developed by the manufacturer Makino Asia Group, the Slim3n model. This equipment operates with three integrated linear axes (3 axis, x-y-z axis) and a two-axis rotational system (2 axis, B + C axis). Originally designed to move its spindle in Cartesian coordinates with extreme precision, the machine features an acceleration of up to 20 m/s<sup>2</sup> and can reach speeds of up to 30 m/min. Also, other features such as constant preloading, multi-plane balancing, vibration minimization, and reduced thermal growth contribute positively to the accuracy of the experimental process (Makino, 2024). Figure 10 presents the Makino Slim3n machine.

**Figure 10 - Makino Slim3n machine**



Source: Own authorship.

The machine's spindle place has been completely adapted for LMD, by the incorporation of A Trumpf Beo D70 optical system. The setup also has a HighNo 4.0 by HD Sonderoptiken metallic powder feeding nozzle, a cooling system for the optics, and a pneumatic powder feeding system. This integration empowers the 3D buildup, coating, and repairing of asymmetrical components. Figure 11 shows the adapted setup installed in the CNC machine.

Figure 11 - Optical system installed in the CNC machine



Source: Fraunhofer ILT archive (2024).

At the Formnext event of 2023 in Frankfurt, Makino launched a specific machine for high-speed laser metal deposition manufacturing modeled as AML500. The machine is thought to be integrated with other devices like robotic arms, inspection cameras, and a milling center for post-processing.

The laser source, from the manufacturer Laserline GmbH and modeled as LDF 4000-8 Fiber Laser, provides power of up to 4 kW, feeding the optical system through an optical fiber that delivers the laser beam to the machine's optical system. According to the beam source specification provided by Laserline the beam parameter product is  $BPP = 8 \text{ mm mrad}$  and the specified wavelength is  $\lambda = 1080 \text{ nm}$ . The focus diameter is the result of the optical set-up consisting of beam source, laser fiber and processing optics. The beam diameter can be adjusted as the

processing optics is equipped with a motorized collimation. Figure 12 presents the laser source LDF 4000-8.

**Figure 12 - Laser power supply LDF 4000-8**



Source: Own authorship.

The Powder Feeder used in this study, manufactured by Metco and designed as the Twin 150-LC model, operates based on a rotating powder disk featuring an annular groove. The speed of the disk determines the rate of powder feed, calibrated to ensure proper filling. A suction bar facilitates efficient and thorough exhaust of the powder into the feed line, where it is conveyed by carrier gas to the designated injection point in the process (Metco, 2024). The feed rate is directly linked to the rotational speed of the powder disk and can be continuously adjusted to any desired level within the established feed range. To maintain precise control, a PID controller is employed to regulate the speed of the disk accurately. Powder Mass Flow (PMF) tests are carried out to measure the rate at which the powder particles are being carried by the carrier gas. The PMF flow is measured in grams per minute (g/min). Figure 13 shows the Twin 150-LC powder feeder.

**Figure 13 - Powder feeder Twin 150-LC**



Source: Metco (2024).

### **3.3 Deposition Process**

The construction of a part using the EHLA3D method involves many steps until getting the final object. The starting point is to define what geometry is going to be built, so then, parameters and deposition strategies can be decided from that.

#### **3.3.1 Parameters Definition**

Deposition parameters are decisive in defining the quality, efficiency, and attributes of components manufactured via LMD. The optimization and refinement of these parameters are imperative to achieve desired outcomes concerning the stability of the process, part geometry, material properties, surface finishing and manufacturing effectiveness. Initial parameters for EHLA3D deposition, derived from prior studies conducted at ILT, have laid the groundwork for the establishment and development of deposition parameters.

The CNC machine delivers an acceleration of up to  $20 \text{ m/s}^2$ , necessitating the utilization of a parameter aimed for the required tool acceleration. Known as the "fly" parameter, it defines the "fly-in" and "fly-out" distances, which represent the lengths added to the start and end of each welding track and are for the required tool

acceleration. Internal ILT parameters were used as reference for the deposition studies.

The initial phase of the EHLA3D process involves the deposition of single beads, laying the groundwork for determining deposition parameters. The objective of the bead study is to verify various characteristics such as bead length, height, deposition area, aspect ratios, dilution area, and dilution depth. This evaluation aims to establish the optimal spacing between beads and the necessary z-increment for constructing a 3D object. Using the provided initial parameters, a single bead of each parameter set was lasered, and metallographic analysis was performed to measure its characteristics. These values now serve as foundational parameters for further parameter development and testing during single layer deposition. Table 1 provides an overview of the deposition parameter sets for each bead. Figure 14 displays an image showing the bead deposition on the substrate, along with a representation of the cross-section cuts A and B utilized for metallographic analysis.

**Table 1 - Parameters set 1, 2 and 3 used on the beads deposition study**

| Parameter set | Beam diameter | PL - Laser power | Vtool - Feed rate | PMF - Powder mass flow | Carrier gas flow | Shielding gas flow | Fly In/ fly out | SOD - Stand off distance |
|---------------|---------------|------------------|-------------------|------------------------|------------------|--------------------|-----------------|--------------------------|
|               | [mm]          | [W]              | [m/min]           | [g/min]                | [l/min]          | [l/min]            | [mm]            | [mm]                     |
| 1             | 1,6           | 1700             | 15                | 15                     | 6                | 10                 | 7               | 10                       |
| 2             | 1,6           | 2900             | 30                | 30                     | 8                | 12                 | 30              | 10                       |
| 3             | 1,2           | 1500             | 15                | 15                     | 6                | 10                 | 7               | 10                       |

Source: Own authorship.

**Figure 14 - Bead deposition on substrate and cross-section cuts representation**

Source: Own authorship.

Through analysis of the cross-section cuts under the microscope, it becomes feasible to discern the measurement characteristics of each bead. Additionally, the bead should exhibit an absence of cracks, pores, and bonding defects.

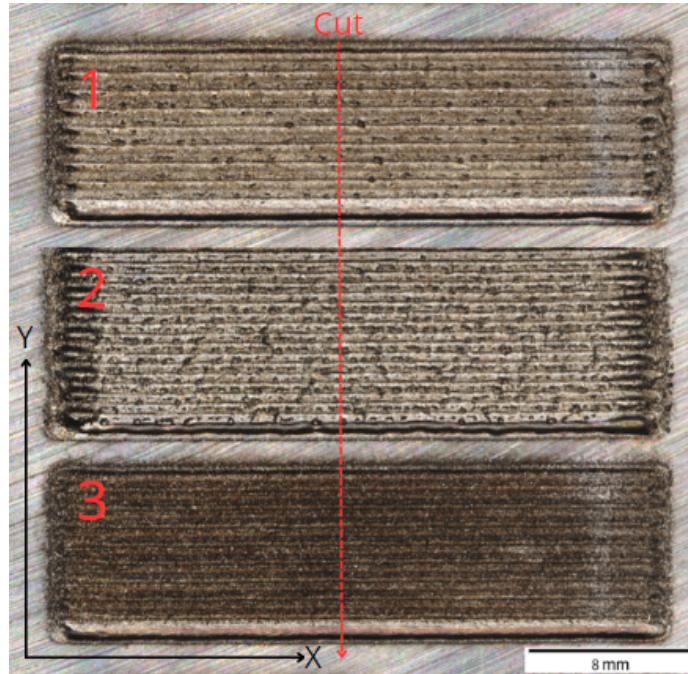
A single layer deposition consists of a group of single tracks deposited onto the substrate next to each other with a specific hatch distance (distance between each bead). It provides essential insights into material behavior, deposition quality, process performance, and heat-affected zone, leading to the refinement of parameters and allowing the parameters as hatch distance and z-increment to be measured and adjusted if necessary.

Initially, the hatch distance is defined as 50% of the bead width, and the z increment is set as the respective height of the bead. The single layer study utilized the same parameter sets established in the bead deposition study. The objective was to assess whether the single layer deposition process is free of defects such as cracks, pores, and lack of bonding, and to determine if the hatch distance between each bead is adequate. The single layer deposition dimension along the x axis is 30 mm, while the dimension of the group of beads connecting to create the single layer (along the y axis) is 8 mm. Figure 15 displays an image of the single layer deposition on the substrate, along with a representation of the cross-section cut used for



metallographic analysis. Table 2 represents the hatch distance used in each parameter set.

**Figure 15 - Single layer deposition of parameters set 1, 2, and 3 and cross-section cut**



Source: Own authorship.

**Table 2 - Hatch distance used in each parameter set**

| Parameter set | Hatch distance |
|---------------|----------------|
|               | [mm]           |
| 1             | 0,45           |
| 2             | 0,50           |
| 3             | 0,45           |

Source: Own authorship.

Block construction represents the third stage in parameter development for the EHLA3D deposition process. It involves stacking multiple single layers, each with identical lengths, on top of one another to create a block geometry. The block is formed when the height of the deposition matches the dimensions of the lengths of the edges. Throughout the block construction process, maintaining a stable Stand-Off-Distance (SOD) at 10 mm is a requirement, making the z-increment a pivotal parameter. This parameter's effectiveness is dependent on others, including bead hatch distance, powder mass flow, feed rate, laser spot size, and laser power.

If the hatch distance is too low, causing beads to be too close to each other, the 3D part may grow in the z direction and come within 10 mm of the nozzle



tip, potentially damaging it. Similarly, inadequate z increment may result in excessive concentrated heat input, leading to defects such as pores. Conversely, if the hatch distance is too large, the beads may form valleys between each other. A z increment higher than the part's growth rate will increase the distance between the part and the nozzle, causing the laser focus to be above the melting pool and resulting in powder inefficiency and bonding defects.

To determine the optimal parameters for hatch distance and z increment, increments of 0,1 mm were tested until the programmed height matched the actual measured build height of the 3D part simultaneously as SOD is kept constant at 10 mm.

In the block deposition study, power variation was implemented with incremental steps of 100 W for each trial. For parameter set 1, the laser power variation ranged from 1400 W to 1800 W. Parameter set 2 began the laser power variation from 2500 W up to 2900 W, while parameter set 3 ranged from 1200 W to 1600 W. Table 3 demonstrates the laser power variation applied for each parameter set of the block deposition.

**Table 3 - Parameters set 1, 2 and 3 laser power variation for blocks deposition**

|                 | Parameter set<br>1 | Parameter set<br>2 | Parameter set<br>3 |
|-----------------|--------------------|--------------------|--------------------|
| Laser power [W] | 1400 - 1800        | 2500 - 2900        | 1200 - 1600        |
| z increment     | 0.19 - 0.3         | 0.25 - 0.3         | 0.2 - 0.3          |

Source: Own authorship.

Conducting a block deposition study allows observation of material and process behaviors. Subsequently, metallography and microscopy analyses can be employed to determine whether the set of parameters yields a 3D part devoid of imperfections and defects such as pores and cracks.

The parameters used in the surface remelting of geometries deposited by EHLA3D were defined in order to address different configurations, allowing for the evaluation of the influence of each parameter on the final measurement results of roughness and waviness of each test field. The parameters variation used for the remelting studies are described in table 4.

**Table 4 - Parameter variation range**

|                                   | Variation range of<br>the walls | Variation range of<br>the flat tops |
|-----------------------------------|---------------------------------|-------------------------------------|
| <b>Laser power [W]</b>            | 400 - 1800                      | 200 - 2700                          |
| <b>Beam diameter [mm]</b>         | 1 - 2 - 3                       | 1 - 2 - 3                           |
| <b>Feed rate [m/min]</b>          | 2 - 5 - 10 - 20 - 30            | 2 - 5 - 10 - 20 - 30                |
| <b>Hatch overlap distance [%]</b> | 30 - 50 - 80                    | 30 - 50 - 80                        |

Source: Own authorship.

### 3.3.2 Geometry Definition

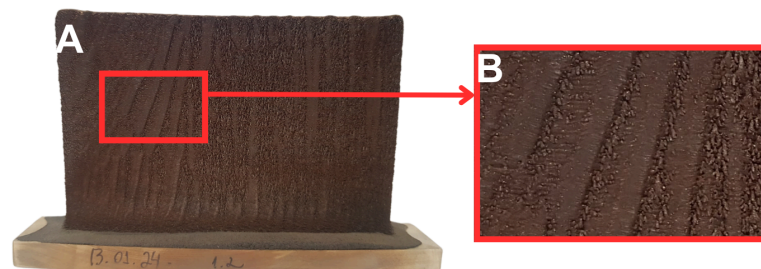
Geometry definition of the 3D part developed for this study aims to have sufficient measurement area from different sides of the probe. To analyze the side surfaces, a cuboid geometry was selected, with dimensions chosen to optimize the utilization of the available substrate area and accommodate as many remelting testing fields as possible. Table 5 presents the dimensions selected for constructing the walls, where the remelting testing fields were positioned on the side surfaces of the wall. Figure 16 and 17 presents 2 different walls deposited with parameter set 3.

**Table 5 - Wall dimensions**

| <b>Length [mm]</b> | <b>Width [mm]</b> | <b>Height [mm]</b> |
|--------------------|-------------------|--------------------|
| 120                | 6,75              | 82,68              |

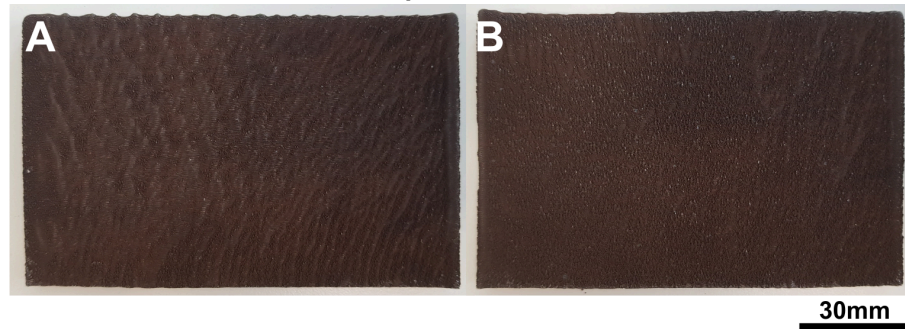
Source: Own authorship.

**Figure 16 - Walls probes deposited with parameter set 3 A) Front of the wall B) Zoom on the deposition defect**



Source: Own authorship.

**Figure 17 - Walls probes deposited with parameter set 3 after cutting the wall apart from the substrate A) Front of the wall showing the deposition defects B) Back of the wall showing very few deposition defects**



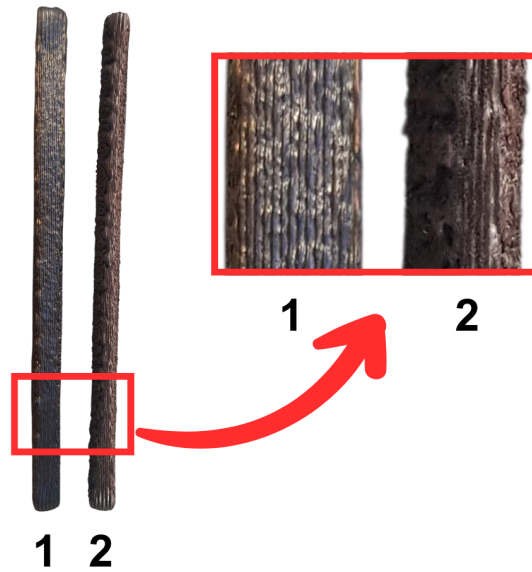
Source: Own authorship.

The final wall exhibited two different thickness measurements: one at the top of the beads and another measurement taken from side to side, which accounted for the powder sprayed on the surface, indicating roughness and the area to be remelted. Measurement at the top of the wall deposited without the extra beads strategy was 5,4 mm, reflecting a loss of thickness of 1,35 mm compared to the programmed value of 6,75 mm. This discrepancy occurred because the first two beads deposited on the edges sprayed along the side of the wall, causing melted powder particles to adhere to the side surface. The measurement of the wall thickness from side to side was 7,86 mm, representing an increase of 1,11 mm from the programmed value and displaying an oxidized appearance.

The measurement at the top of the wall deposited with the extra beads strategy was 6,85 mm, reflecting a gain of thickness of 0,1 mm compared to the programmed value of 6,75 mm, and demonstrating that the extra bead strategy prevented the loss of thickness of the wall. Thickness from side to side was 7,85 mm, a very similar dimension when comparing to the measurement from side to side of the wall without the extra bead on the long edge.

Figure 18 shows a top view of the wall depositions, comparing a wall deposited using linear hatching deposition strategy and a wall deposited with linear hatching deposition with extra beads along the long edges. Table 7 presents the measurements of the wall deposited.

**Figure 18 - Top view of the walls deposition 1) Wall deposited with extra beads along the long edges 2) Wall deposition without extra beads along the long edges**



Source: Own authorship.

In this setup, each wall can accommodate 15 test fields, each measuring 17 x 17 mm on every side. However, to mitigate the risk of cracks on the remelted fields caused by deformation resulting from plate warping during the remelting technique, only one side was utilized to position the test fields.

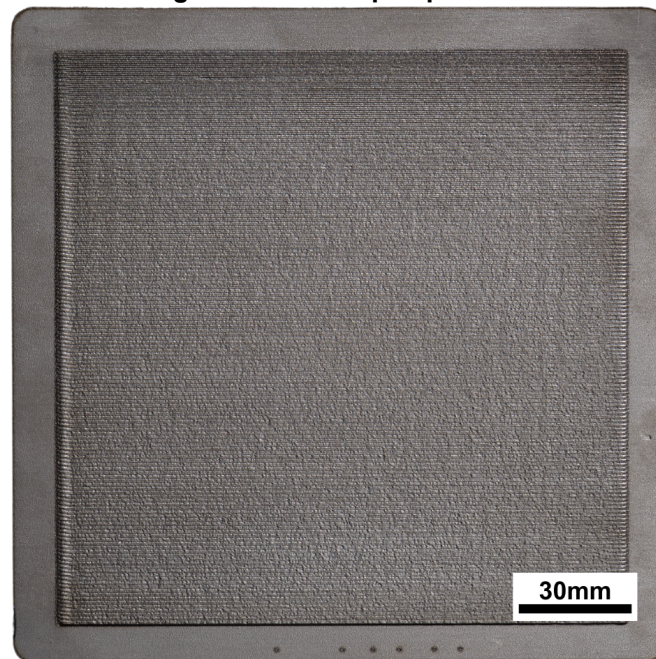
The other surface that emerges from the fabrication of a 3D object is the flat top, marking the last layer of the deposition process. The area designated for the remelting study on flat tops comprises only four layers. The dimensions of the flat top deposition permit the placement of 36 test fields measuring 17 x 17 mm on each plate, as outlined in Table 6.

| Table 6 - Flat top dimensions |            |             |
|-------------------------------|------------|-------------|
| Length [mm]                   | Width [mm] | Height [mm] |
| 130                           | 130        | 1,06        |

Source: Own authorship.

A total of three flat-top depositions were constructed, with one sample left as a showcase, while the other two samples underwent remelting studies. Figure 19 presents a flat top deposition.

**Figure 19 - Flat top deposition**



Source: Own authorship.

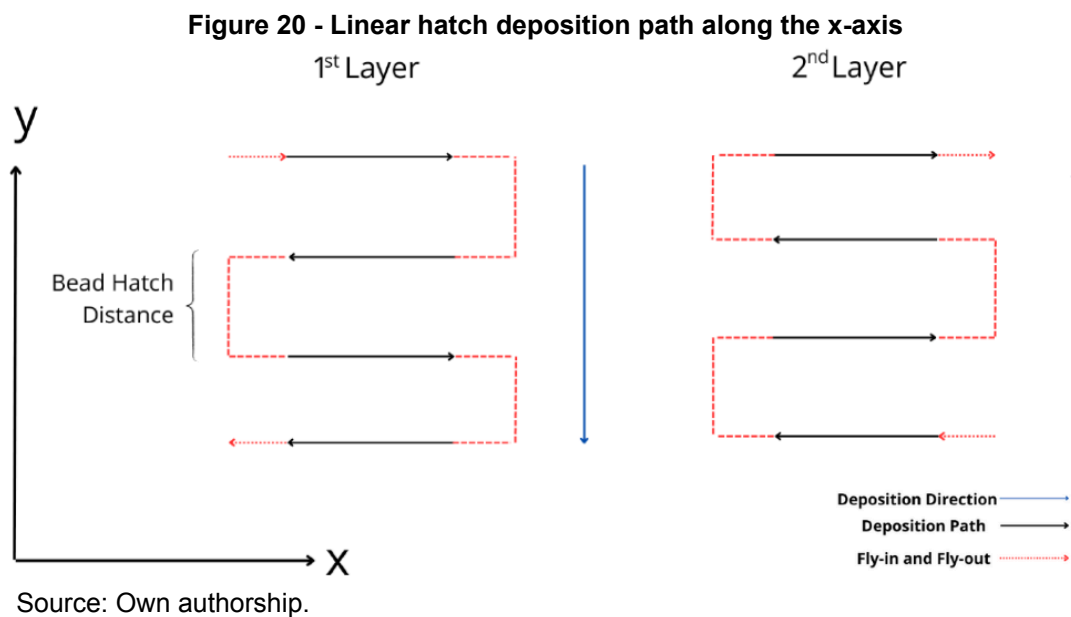
### 3.3.3 Deposition Strategy

Deposition strategies are used for managing heat input and thermal gradients, preventing distortion, and ensuring dimensional accuracy. A common technique to distribute heat input evenly is to initiate deposition at opposing coordinates in each layer. The deposition direction of each layer is carefully selected to distribute energy throughout the process, minimizing residual stresses and distortion. Simultaneously, controlling cooling rates promotes uniform grain growth and distribution, resulting in enhanced mechanical properties such as strength, ductility, and fatigue resistance. This study experimented with three different strategies:

- Linear hatching deposition;
- 90° cross-hatching deposition;
- Linear hatching deposition with extra beads on long edges.

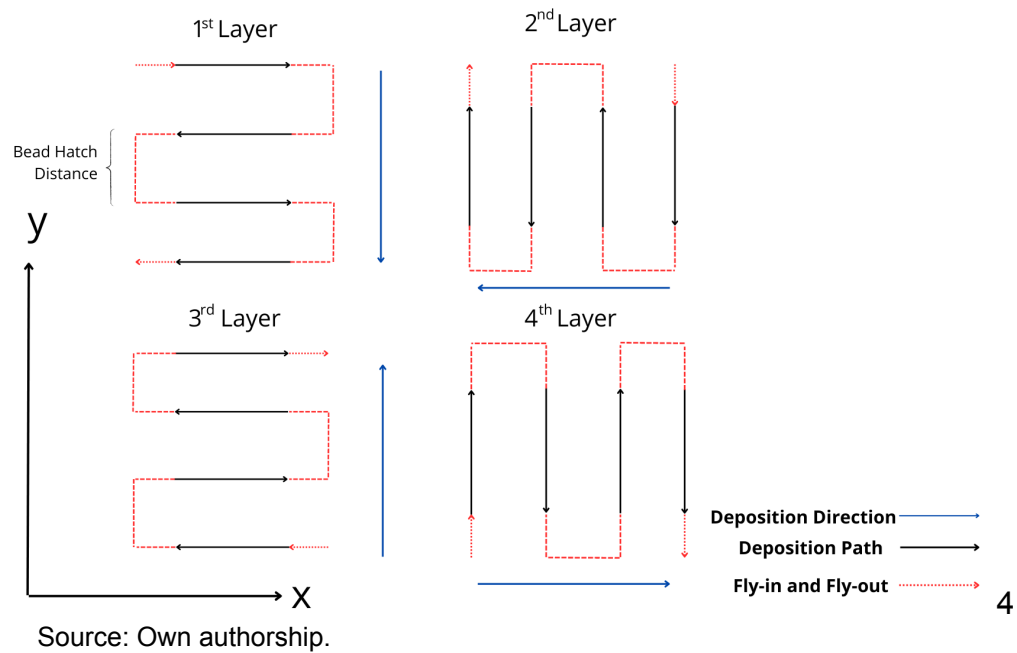
### 3.3.3.1 Linear Hatching Deposition

The deposition path of the linear hatching along the x-axis can be easily defined in an optimized G-code by setting the length distances of the x and y coordinates. To ensure an even distribution of energy deposited on the part during the process, an alternating deposition direction in the y coordinate was chosen. Figure 20 illustrates the linear hatch deposition path along the x-axis.



### 3.3.3.2 90° Cross-hatching Deposition

Another strategy to mitigate uneven heat distribution defects is to alternate the deposition direction by a 90° angle between every layer. “It is evident that by increasing rotation angle the overall appearance of the molten pool and the distribution, number and size of cellular and fiber sub-structures were affected by the temperature dissipation of the deposition layer.” (Li, Y., et al., 2023, p. 4). Also according to the study developed by Li, Y. et al. (2023, p. 4), the overall appearance of the 90° cross-hatching deposition demonstrated the most regular morphological characteristics compared to linear deposition strategies. Figure 21 illustrates the trajectory path of a 90° cross-hatching deposition.

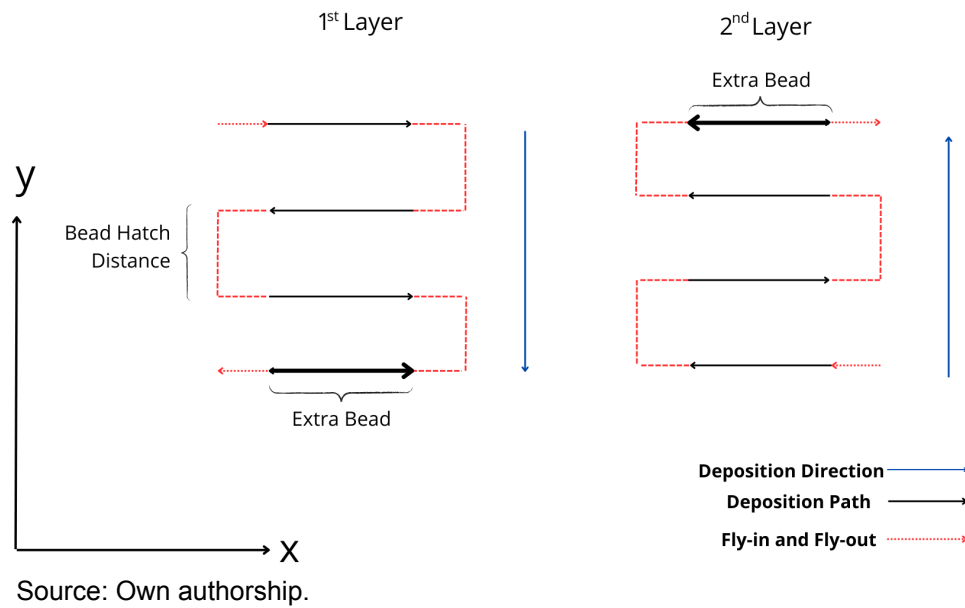
**Figure 21 - 90° cross hatch deposition path**

### 3.3.3.3 Linear Hatching Deposition with Extra Welding Beads

Depositing along the x axis can result in dimensional inaccuracies as the object may experience slight dimensional shrinkage during the build-up along the z axis. Additionally, the edges of the part may become oxidized as the initial beads of each layer spray melted powder particles onto the side surfaces. One improvement to the linear hatching deposition strategy involves utilizing extra beads only along the long edges, facilitating the build up of a 3D object with more precise geometry, even as the part grows in the z direction. An extra welding bead was deposited every layer, alternating the edge that received an extra bead every layer. A total of 9 walls were constructed using this deposition strategy. One of the walls underwent sandblasting to assess whether removing surface oxides would enhance the remelting process and results. Figure 22 presents the linear hatching deposition with extra welding beads along the long edges of the defined probe geometry.



**Figure 22 - Linear hatching deposition with 1 extra welding bead in every layer**



### 3.4 Laser Remelting

This section provides a detailed overview of the remelting procedures conducted in this study. It covers the machinery used, the filters applied to enhance outcomes, and the strategic development of the Design of Experiments (DOE) to systematically investigate different parameters. Furthermore, it elaborates on the remelting process itself, highlighting key methodologies and techniques to offer a comprehensive understanding of the experimental procedures.

DOE sheet is a structured document used to plan and organize the implementation of a systematic approach to determine how various factors affect a response variable of interest, in this case, Roughness  $Sa$  and Waviness  $Wa$ .

The DOE was designed in 3 main stages. The variables analyzed are the Laser Spot Size (LSS) (varying between 1, 2, and 3 mm), the feed rate (2, 5, 10, 20 e 30 m/min), and the beam laser power (from 300 to 1800 W) increasing 100 W for every new laser power value. In stage 2, bead overlap hatch distance (varying between 30%, 50%, and 80% bead overlap) was included in the parameters combination.

An indispensable parameter employed in all remelting processes investigated in this study is the utilization of argon as an inert gas. This is particularly crucial due to the generation of numerous gases during the process, which may contain impurities capable of contaminating the material, thereby promoting oxidation



or chemical alterations that could compromise its performance and integrity. Additionally, the use of shielding gas offers the advantage of preserving the integrity of the protective lenses within the optical system that could distort the focus of the laser and cause loss of efficiency of the beam if any damage is caused. This is achieved by preventing molten metal particles from splattering onto the lenses, as the shielding gas is consistently directed in the same path as the laser beam.

Table 7 displays one of the experimental test combinations implemented in stage 2, wherein only the hatch overlap distance varies while the other parameters remain constant.

| <b>Table 7 - Remelting parameters</b> |                           |                          |                           |                  |                              |
|---------------------------------------|---------------------------|--------------------------|---------------------------|------------------|------------------------------|
| <b>Run</b>                            | <b>Beam Diameter [mm]</b> | <b>Feed rate [m/min]</b> | <b>Hatch Distance [%]</b> | <b>Power [W]</b> | <b>Shielding gas [l/min]</b> |
| <b>1</b>                              | 1                         | 2                        | 30                        | 400              | 6                            |
| <b>2</b>                              | 1                         | 2                        | 50                        | 400              | 6                            |
| <b>3</b>                              | 1                         | 2                        | 80                        | 400              | 6                            |

Source: Own authorship.

The DOE development was distributed in 3 stages as described below.

- A. Stage 1: Application of 147 different parameter combinations;
- B. Stage 2: Application of 111 different parameter combinations;
- C. Stage 3: Selection of the 30 best parameter combinations.

In stage 1, a total of 147 testing fields were conducted, each measuring 15 x 7 mm. Some parameter combinations that failed to remelt a testing field within a certain range were automatically excluded from further consideration. This elimination process discarded parameters that theoretically provided less energy input compared to the tested combinations, such as higher feed rates, smaller overlap distances, and larger LSS, as according to the conducted experiments these parameter sets provide too less energy input for a complete remelt.

During the practical experiment, results were analyzed through visual inspection, by a pure qualitative evaluation. Parameters were categorized as either promising or not for further testing in stage 2. Observations such as pore detection, plasma formation, and the percentage of remelted area were recorded as data during

the process. The qualitative analysis of parameters throughout the experiment is presented in table 8.

**Table 8 - Qualitative evaluation of parameters observed during the remelting process**

| Remelting Status                 | Plasma Status                            | Pores status                      |
|----------------------------------|------------------------------------------|-----------------------------------|
| NR - Not Remelted (0 - 75%)      | NP - No Plasma (Only melt pool)          | NP - No pores (0 pores)           |
| PR - Partially Remelted (76-95%) | LP - Low Plasma (0,1 - 3 mm)             | MP - Medium Pores (up to 5 pores) |
| FR -Fully Remelted (95 - 100%)   | MP - Medium Plasma (3,1 - 7 mm)          | HP - High Pores (Above 5 pores)   |
|                                  | HP - High Plasma (7,1 - 10 mm)           |                                   |
|                                  | EP - Extremely High Plasma (Above 10 mm) |                                   |

Source: Own authorship.

The 147 attempts conducted in stage 1 were filtered to isolate the most effective parameter combinations observed during the process. These optimal combinations exhibited minimal or low plasma formation, remelted areas exceeding 75%, and negligible or minimal pore formation. Following the application of this filter, all combinations yielding satisfactory visual results underwent microscopic analysis to identify any potential cracks. From this filtered selection and the microscope examination conducted in stage 1, 37 of the best parameters were deemed eligible for further testing in Stage 2.

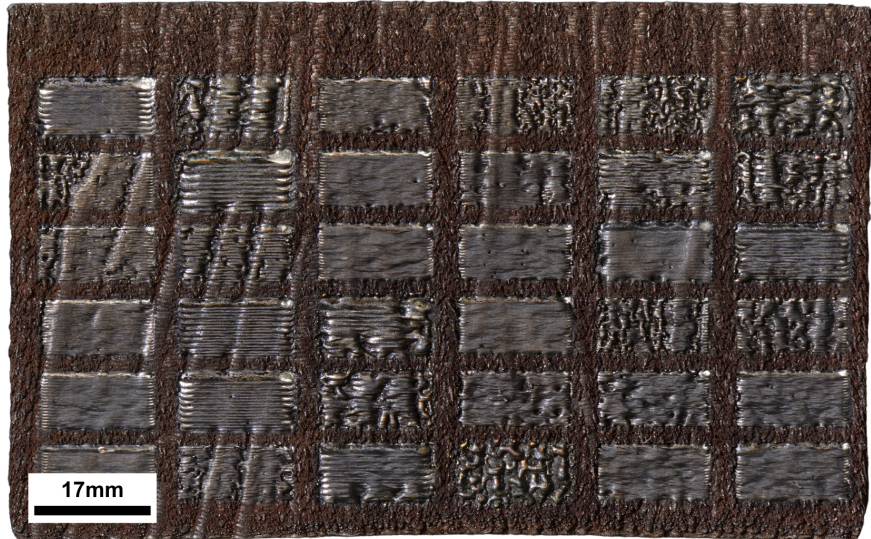
In stage 2, an additional variable, the bead hatch distance overlap, was introduced. This led to a total of 111 eligible combinations for stage 2 experimentation. Similar to stage 1, the logical analysis employed in stage 2 discarded results that did not fully remelt the test field. Stage 2 encompassed testing 74 different parameter combinations, with the same analysis criteria applied throughout the process at stage 1. After filtering the best results and analyzing test fields under a microscope, the 30 most promising outcomes were identified for further investigation in stage 3.

Parameters selected for stage 3 comprised official combinations applied to test fields measuring 17 x 17 mm with two distinct characteristics: a predominantly rough surface (without deposition defects) and another exhibiting roughness and waviness due to material accumulation during the process, resulting in deposition

defects. From the stage 3 results, 10 combinations were chosen for application on a sandblasted wall to assess the impact of surface oxide cleaning before remelting.

Results obtained from the exploration of the DOE sheet originated the parameters used in the real test fields of the remelting study of the walls. To evaluate the best parameter combination possible, remelting fields of 17 x 7 mm were remelted on both sides of 4 of the walls previously built. Each side of a wall comported 36 testing fields, resulting in a total of 288 testing fields used in stages 1 and 2 of the DOE parameter development. The other 5 walls remained intact for the remelting study considering the best parameters combination tested in the DOE sheet. Figure 23 shows an image of one of the walls used in the DOE parameters exploration.

**Figure 23 - Wall used in the DOE parameter exploration with 36 testing fields**

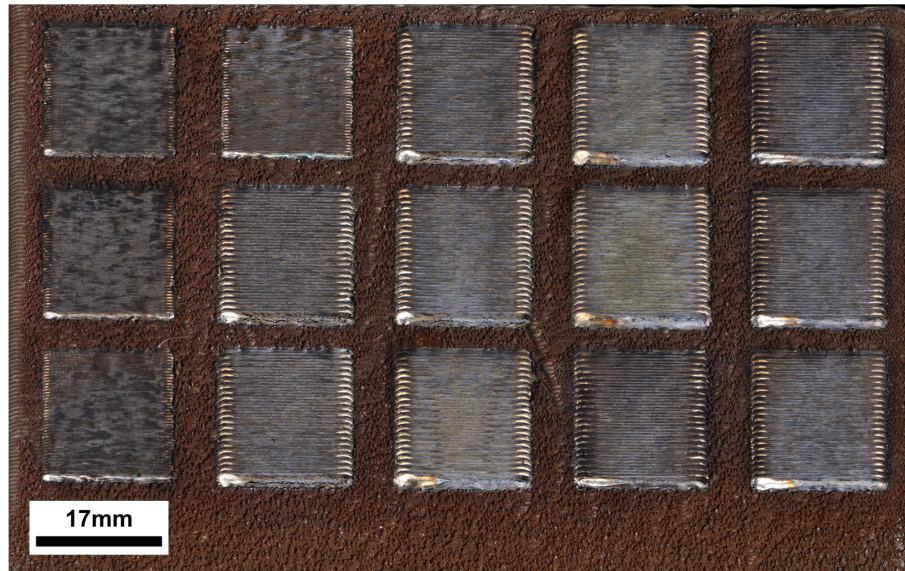


Source: Own authorship.

At stage 3 of the DOE, the top 30 parameters were implemented on test fields measuring 17 x 17 mm each. However, the remelting process caused warping of the walls, leading to the utilization of only one side of each wall for the stage 3 parameter combinations. Each wall accommodated 15 testing fields, necessitating the remelting of the surfaces of two different walls to apply all parameters selected for stage 3 of the DOE. To analyze surfaces with varying characteristics, four walls were chosen for the remelting application of stage 3 parameters: two with mostly rough surfaces (with very few deposition defects), and another with surfaces exhibiting roughness and increased waviness due to material accumulation resulting in deposition defects. Comparing the remelting results of these two different surface

characteristics provides valuable insights. Figure 24 illustrates one of the four walls with the parameters set in stage 3 of the DOE.

**Figure 24 - Wall with remelted testing fields from stage 3 of the DOE**



Source: Own authorship.

From the parameters selected on stage 3 of the DOE development sheet, 10 parameter combinations that had the best visual aspects were chosen to be applied to a sandblasted wall. This can lead to a comparison to determine if the removal of the oxide can positively affect the results. Figure 25 shows the sandblasted wall with the remelting fields applied to it.

**Figure 25 - Sandblasted Wall with Remelting testing fields**



Source: Own authorship.

Parameter development for flat top surfaces was conducted and analyzed throughout the remelting process. The dimensions of the remelted area matched

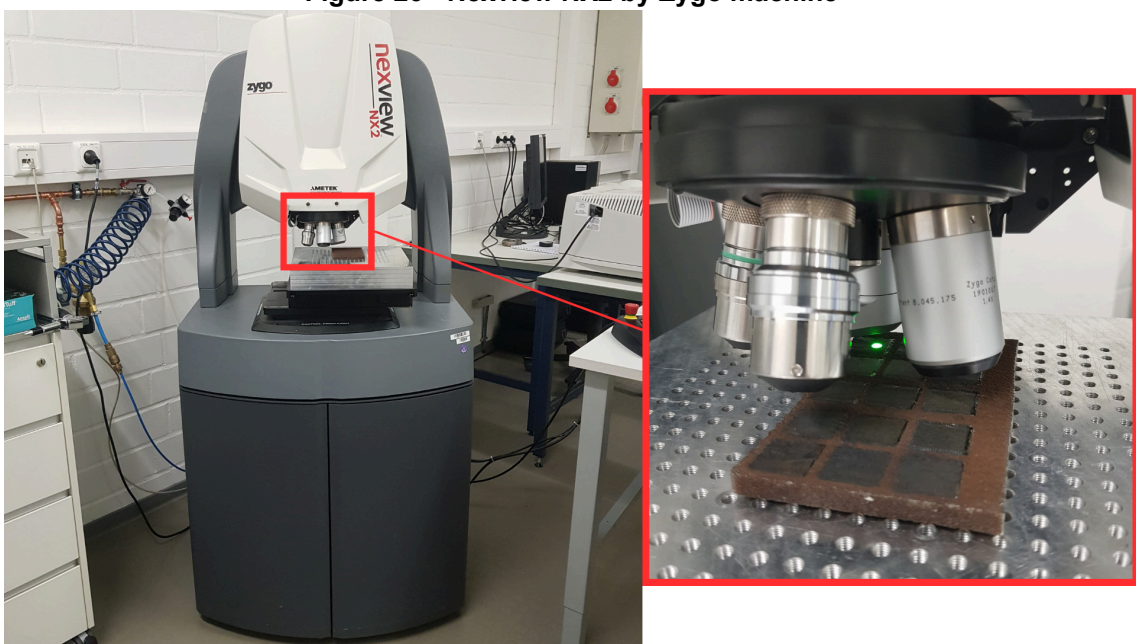


those in stage 3 of the DOE, measuring 17 x 17 mm. Ranging from 300 to 2700 W with incremental steps of 100 W in PI, and varying other parameters for each PI, such as bead hatch overlap distance, LSS, and feed rate (see table 5), the same principles of the DOE experiment were applied. Combinations of parameters that failed to yield promising results were discarded, and the study proceeded with the next combinations. The flat-top parameter development resulted in 72 testing fields, with roughness and waviness measured and compared to the initial reference measurements of the surface before laser remelting was applied.

### 3.5 Analysis Methodology

The available white light interferometer machine is the Nexview NX2 by Zygo, an optical metrology system designed for precise surface profiling and measurements. Integrated with the MX software, this machine facilitates adjustment of image acquisition settings and enables data processing and analysis. It allows for detailed analyses, including characterization of surface roughness and waviness. Measurements of roughness and waviness were conducted both before and after the laser remelting application. Figure 26 displays an image of the Nexview NX2 by Zygo machine.

**Figure 26 - Nexview NX2 by Zygo machine**

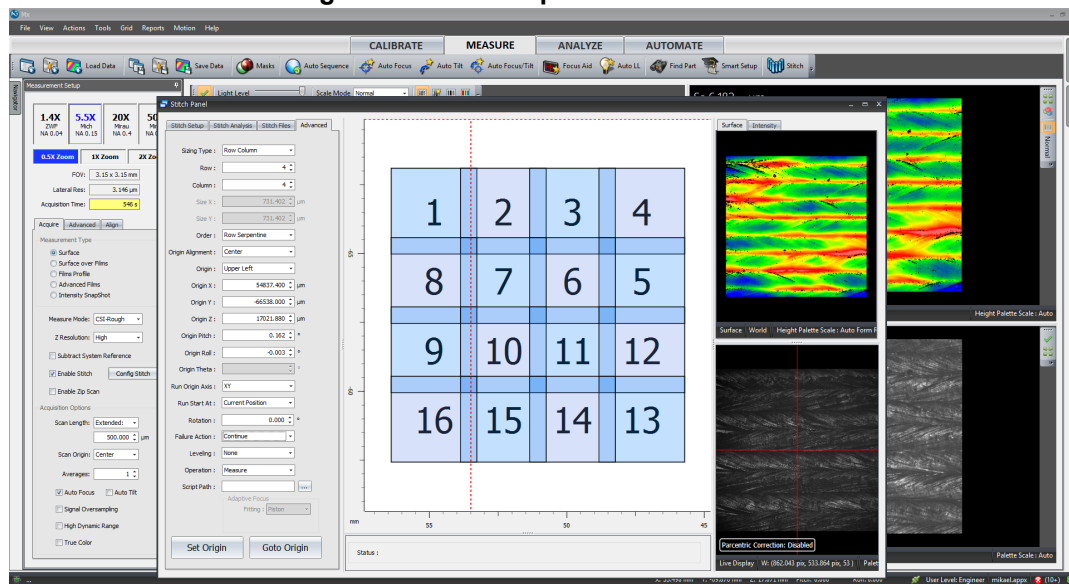


Source: Own authorship.

To facilitate measurements in the WIM device, the walls were cut from the substrate plate. Each side of every wall was measured once, and this result served as the reference. Similarly, on the flat tops, a central area of the surface was measured and used as a reference for comparison with measurements taken after remelting.

Upon positioning the sample on the WIM machine's table, the software required adjustment based on the part being measured. In pursuit of more precise measurements of the area, an image stitching configuration was utilized, resulting in a 4 x 4 matrix to be measured for each remelted test field. Figure 27 depicts the interface of the MX software used in the parameter setting window, while Table 9 outlines the parameters adjusted for the measurements.

**Figure 27 - MX setup software Interface**



Source: Developed by author (2024).

**Table 9 - Parameters settings used for WIM measurements**

|                                |             |
|--------------------------------|-------------|
| <b>Magnification lens</b>      | 5,5x        |
| <b>Zoom</b>                    | 0,5x zoom   |
| <b>FOV [mm]</b>                | 3,15 x 3,15 |
| <b>Lateral resolution [μm]</b> | 3,146       |
| <b>Acquisition time [s]</b>    | 546         |
| <b>Measuring type</b>          | Surface     |
| <b>Measuring mode</b>          | CSI-Rough   |
| <b>Z resolution</b>            | High        |

|                                                        |       |
|--------------------------------------------------------|-------|
| <b>Stitching matrix</b>                                | 4 x 4 |
| <b>Scan length Extended [<math>\mu\text{m}</math>]</b> | 1500  |
| <b>Autofocus</b>                                       | On    |

Source: Own authorship.

Once the measurements are completed, it is necessary to apply the appropriate filter to obtain the final roughness ( $Sa$ ) and waviness ( $Wa$ ) measurements of each test field. These results after remelting will subsequently be compared to the reference results obtained from the surfaces before remelting. The parameters for setting up the filter to obtain each variable result are illustrated in Table 10.

**Table 10 - Filters applied after the WIM measurements**

|    |                                |                              |
|----|--------------------------------|------------------------------|
| Sa | Filter type                    | Spline                       |
|    | Filter                         | Band pass                    |
|    | Type                           | Robust gaussian spline fixed |
|    | Mode                           | Period                       |
|    | Short period [ $\mu\text{m}$ ] | 6,296                        |
|    | Long period [ $\mu\text{m}$ ]  | 2500                         |
| Wa | Short period [ $\mu\text{m}$ ] | 2500                         |
|    | Long period [ $\mu\text{m}$ ]  | 10702,695                    |

Source: Own authorship.

The parameters set for measuring the remelted testing fields are the same as the parameter settings used for the initial roughness and waviness reference measurements, as described in tables 8 and 9 in section 3.4.4. A total of 142 remelted fields were measured and compared with the reference values.

Results obtained from the filter application after the surface measurements include values of roughness  $Sa$  and waviness  $Wa$ . Subsequently, these results are linked to their respective remelting parameters, such as beam diameter, feed rate, hatch overlap, and laser beam power. This linkage of results to their remelting parameters allows for the detection of the influence of each parameter on the process results. Sections dedicated to each parameter variation are presented alongside their results below.

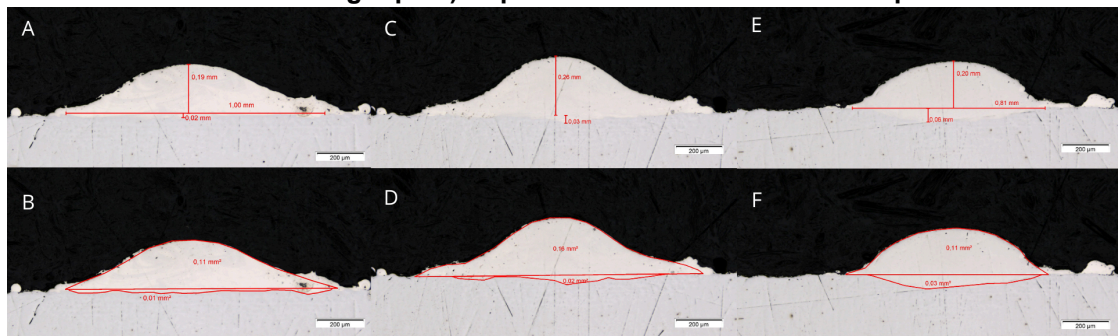
## 4 RESULTS

This chapter presents the results derived from the definitive experimental trials conducted in each segment of the study. It also provides an in-depth discussion and analysis of each topic covered.

### 4.1 Beads Deposition

The figure presented below belongs to the cross-section cut A. Figure 28 shows the bead measurements comparisons between parameter set 1, 2, and 3, where figure A and B shows measurement values for parameter set 1, C and D values for parameter set 2 and D and E measurement values for parameter set 3. Table 11 presents the measurements obtained from the all parameters set demonstrated in figure 28.

**Figure 28 - Cross-section cut A of bead deposition where A) Deposition height, length and dilution height of p1 B) Deposition area and dilution area of p1 C) Deposition height and dilution height of p2 D) Deposition area and dilution area p2 E) Deposition height, length and dilution height p3 F) Deposition area and dilution area p3**



Source: Own authorship.

**Table 11 - Bead Measurements of parameter set 1, 2 and 3**

|                                         | Parameter set 1 | Parameter set 2 | Parameter set 3 |
|-----------------------------------------|-----------------|-----------------|-----------------|
| <b>Length [mm]</b>                      | 1,00            | 1,07            | 0,81            |
| <b>Height [mm]</b>                      | 0,19            | 0,26            | 0,20            |
| <b>Dilution depth [mm]</b>              | 0,02            | 0,03            | 0,06            |
| <b>Deposition area [mm<sup>2</sup>]</b> | 0,11            | 0,16            | 0,11            |
| <b>Dilution area [mm<sup>2</sup>]</b>   | 0,10            | 0,02            | 0,03            |



Source: Own authorship.

A comparison between parameter sets for beads 1 and 3 reveals the direct influence of LSS on the length of the bead, as a larger beam diameter produces a longer bead, while the bead height and deposition area remain relatively similar. LSS also impacts the melting pool, with a smaller beam diameter resulting in a larger dilution area and depth.

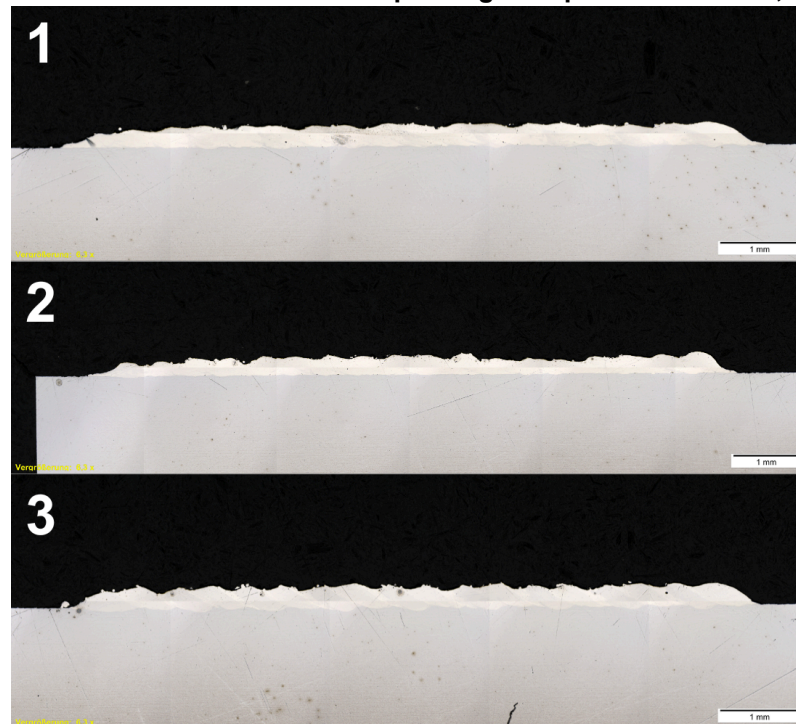
In the deposition at 30 m/min, the laser power was set at 2700 W. Bead measurements indicate that a higher powder mass flow compensated for the increased feed rate, resulting in a wider and taller bead compared to parameter sets 1 and 3. The deposition area was also larger than in parameter sets 1 and 3, while the dilution area and depth were nearly identical to parameter set 1.

## **4.2 Single Layers Deposition Study**

Upon analyzing the images, it was determined that the samples were free of defects. Another important analysis involves measuring the SOD from the nozzle to the part after deposition, which remained constant at 10 mm. Maintaining a constant SOD is essential, so that if the beads are positioned too closely, the SOD may increase excessively, resulting in wear to the tip of the powder jet nozzle. Conversely, positioning the beads too far apart can lead to deep valleys between them, resulting in high waviness and process instability due to an increase in the SOD. The hatch distances used in the single layer deposition are detailed in table 14.

Figure 29 shows microscopic images of the cross-section cut of the single layer deposition. The parameter sets displayed below are consistent with those utilized in previous studies.

**Figure 29 - Cross-sections microscope images of parameters set 1, 2, and 3**



Source: Own authorship.

### 4.3 Block Deposition Study

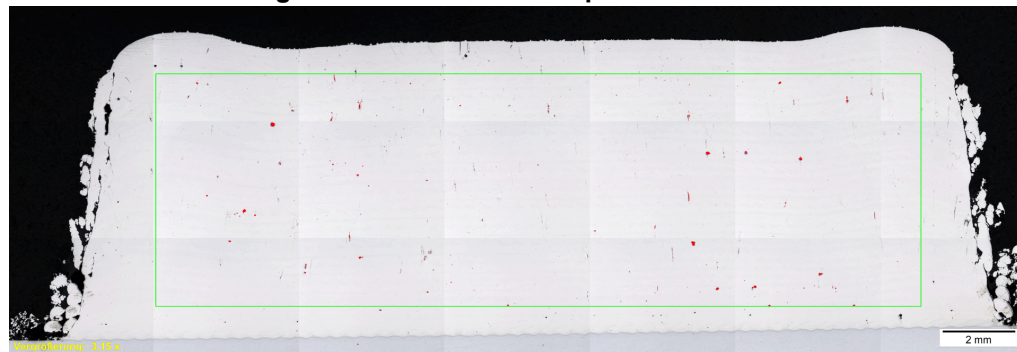
In the block deposition study, power variation was implemented with incremental steps of 100 W for each trial. For parameter set 1, the laser power variation ranged from 1400 W to 1800 W. Parameter set 2 began the laser power variation from 2500 W up to 2900 W, while parameter set 3 ranged from 1200 W to 1600 W.

Bead hatch distance and z-increment parameters are determined based on bead measurements, with the hatch distance set as half of the bead length and the z-increment as the bead height. These parameters are adjusted based on the results of the experimental procedure. If the hatch distance is too low, causing beads to be too close to each other, the 3D part may grow in the z-direction and come within 10 mm of the nozzle tip, potentially damaging it. Similarly, inadequate z-increment may result in excessive concentrated heat input, leading to defects such as pores. Conversely, if the hatch distance is too large, the beads may form valleys. A z-increment higher than the part's growth rate will increase the distance between the

part and the nozzle, causing the laser focus to be above the melting pool and resulting in powder inefficiency and bonding defects.

To determine the optimal parameters for hatch distance and z-increment, increments of 0.1 mm were tested until the programmed height matched the actual measured build height of the 3D part. The final parameters for block deposition are presented below. Figure 30 illustrates the block constructed with parameter set 1.

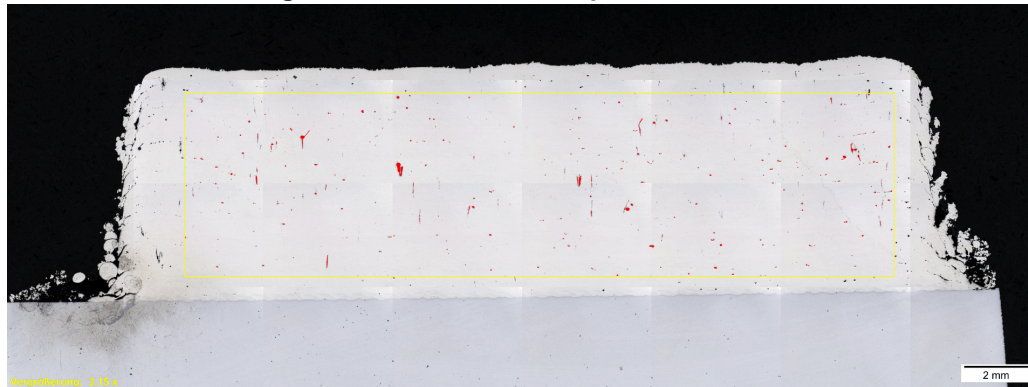
**Figure 30 - EHLA3D block parameter set 1**



Source: Own authorship.

Figure 31 shows the block constructed with parameter set 2.

**Figure 31 - EHLA3D block parameter set 2**



Source: Own authorship.

Figure 32 shows the block constructed with parameter set 3.

**Figure 32 - EHLA3D block parameter set 3**

Source: Own authorship.

Table 12 displays the measurements obtained from microscopic analysis.

**Table 12 - Block measurements for parameter sets 1, 2 and 3**

| Parameter set 1    |        | Parameter set 2    |        | Parameter set 3    |        |
|--------------------|--------|--------------------|--------|--------------------|--------|
| Height min [mm]    | 8,979  | Height min [mm]    | 6,912  | Height min [mm]    | 7,589  |
| Height max [mm]    | 8,336  | Height max [mm]    | 7,246  | Height max [mm]    | 7,856  |
| Length bottom [mm] | 29,071 | Length bottom [mm] | 25,336 | Length bottom [mm] | 25,143 |
| Length top [mm]    | 26,356 | Length top [mm]    | 23,978 | Length top [mm]    | 23,368 |
| Porosity [%]       | 0,1    | Porosity [%]       | 0,33   | Porosity [%]       | 0,05   |

Source: Own authorship.

Geometric analysis shows that parameter set 3 has a better 3D part regarding dimensional values, a better geometric deposition aspect, and fewer pores than parameter sets 1 and 2.

Crack formation is a common concern in powder based LMD processes and can significantly impact the structural integrity and quality of fabricated parts. "In these processes, one of the most common defects that limit final part quality is cracks, as they can considerably reduce the mechanical strength of the component." (Prieto et al., 2020, p.1). Understanding the factors contributing to crack formation is essential for optimizing the EHLA3D process and ensuring the reliability of manufactured components. Higher deposition speeds can lead to shorter exposure times to heat, reducing the duration of thermal cycling and potentially minimizing the development of thermal stresses that contribute to crack formation. Additionally, rapid

cooling rates associated with high deposition speeds may help mitigate the propagation of cracks by promoting more uniform solidification and reducing the time for crack initiation and propagation. “The smaller heat input results in smaller risk of heat induced defects like hot cracks and, in addition to that, the cooling rate can be adjusted according to the material by variation of the feed rate.” (Ko, Zhang and Schopphoven, 2023, p. 1).

#### 4.4 90° Cross-hatching Wall Deposition

The parameters and dimensions utilized in the x-axis deposition wall were maintained for the 90° cross-hatching deposition wall. In the cross-hatching strategy, the y axis was employed to construct the long beads (120,0 mm), while the x axis was utilized for the short beads (6,75 mm). However, this process required more time to complete the final part compared to the x axis deposition, as the deposition along the x-axis produced short beads matching the wall thickness of 6,75 mm.

The cross-hatching strategy was discarded due to a geometrical defect formation which resulted in a rounded shape. This effect is presented in Figure 33.

**Figure 33 - A) Top view of the 90° cross-hatching wall deposition. B) Side view of the 90° cross-hatching wall deposition**



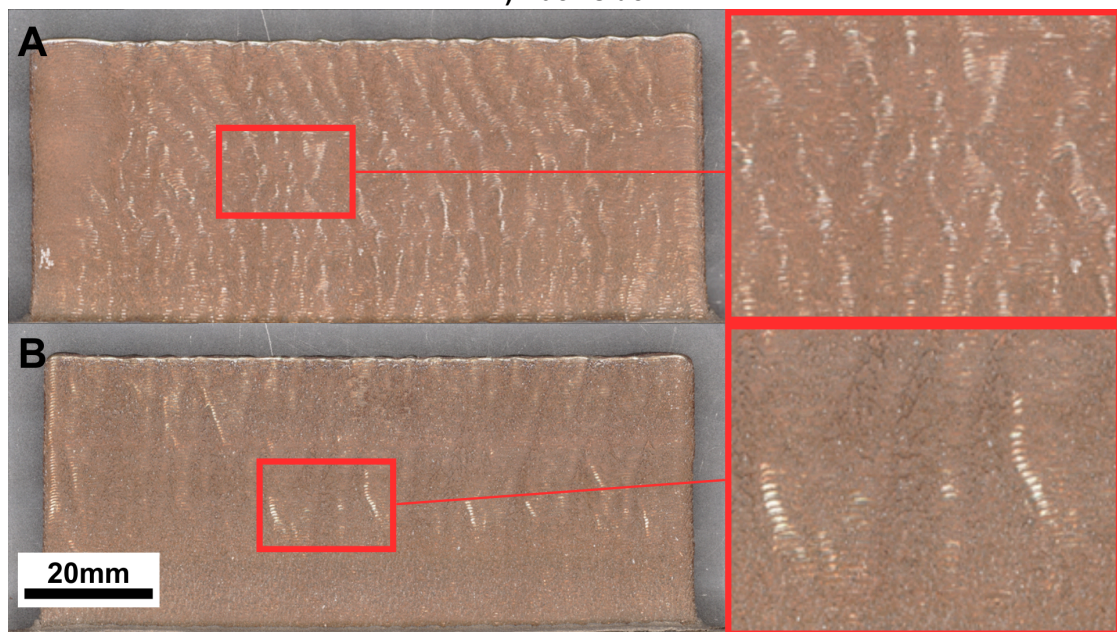
Source: Own authorship.



#### 4.5 Linear Hatching Wall Deposition with Extra Welding Beads

Material accumulation during the process resulted in deposition defects on the front side of the wall, while the back side displayed very few deposition defects, leading to elevated waviness on the front side compared to the back. Measurements from the WIM confirmed this higher waviness on the front side. Figure 34 shows an image of the front resulted wall deposited with the extra welding bead strategy, chosen for further investigation.

**Figure 34 - Wall constructed with one extra welding bead at every layer strategy A) Front side  
B) Back side**



Source: Own authorship.

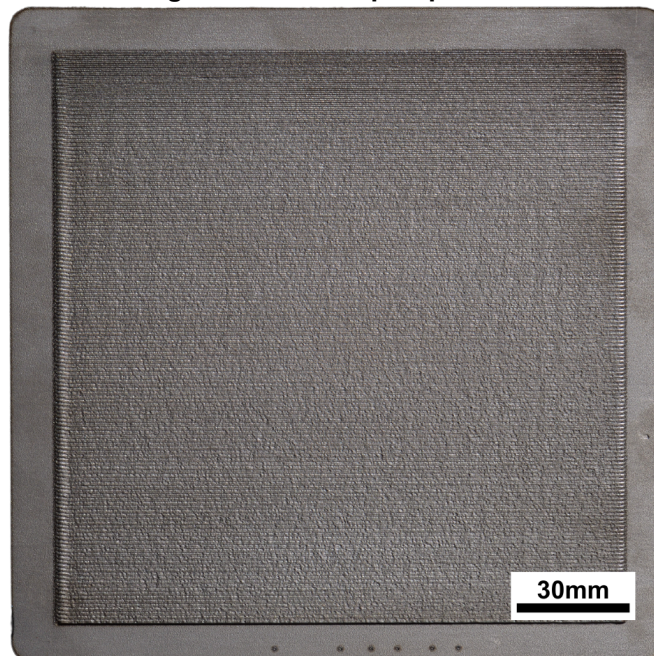
Consistently, each wall exhibited predominantly rough back sides with minimal deposition defects, while the front sides showed increased waviness and numerous deposition defects. This could be due to a slight misalignment of the powder jet nozzle's focus or a high carrier gas flow, promoting material accumulation at specific deposition points. Additionally, the extra welding bead at each layer may have contributed to material accumulation.

Subsequently, all walls were transported to the mechanical laboratory, where the substrate was removed to facilitate roughness and waviness measurements.

#### 4.6 Flat Top Deposition

The parameter was used for both probe geometries. The flat top deposition involves stacking four single layers with a cross hatching strategy. Figure 35 illustrates an image of the flat-top deposition.

**Figure 35 - Flat Top Deposition**



Source: Own authorship.

#### 4.7 Reference Roughness and Waviness Measurements

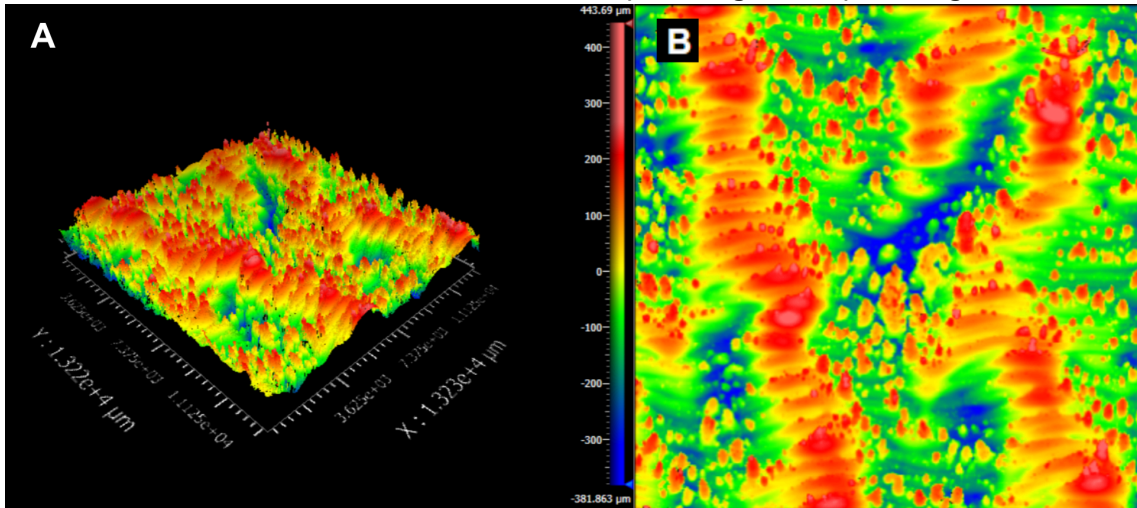
This measurement took approximately 90 minutes due to the high initial roughness of the samples.

When the measuring was done, the filters described in section 5.4.4 were applied to the results to isolate the final measurements for roughness and waviness. Image 36 presents a WIM result image demonstrating a reference measurement of a deposition defect. Image 37 shows an example of the resulting image from the



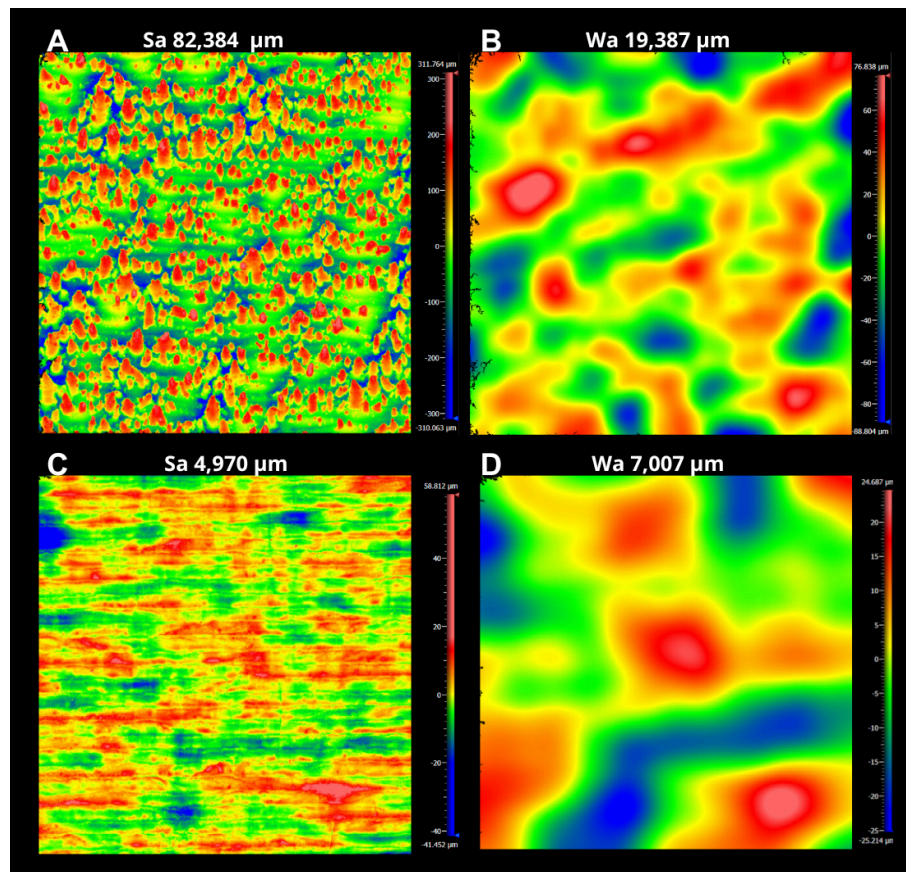
measurement and comparison between the reference wall without deposition defects and the remelted testing field number 10 after the filters were applied.

**Figure 36 - Result image from the WIM measurement demonstrating a deposition defect that caused increased waviness where A) 3D image and B) 2D image**



Source: Own authorship.

**Figure 37 - Result Image of the WIM Measure for  $S_a$  and  $W_a$  where: A) Reference Wall B)  $W_a$  Reference Wall C)  $S_a$  Wall remelting test field number 10 D)  $W_a$  Wall remelting test field number 10**



Source: Own authorship.



The flat top initial roughness and waviness measurements were based on the same principle as the reference measurements of the walls, including the same parameter set and filter application. A measuring field near the center of the deposited flat top was measured and taken as a reference for further comparison to the remelted testing fields. Table 13 presents an overview of the reference measurements results.

**Table 13 - Reference measurement results for roughness and waviness**

|                                       | <b>Sa [<math>\mu\text{m}</math>]</b> | <b>Wa [<math>\mu\text{m}</math>]</b> |
|---------------------------------------|--------------------------------------|--------------------------------------|
| <b>Reference wall without defects</b> | 82,384                               | 19,387                               |
| <b>Reference wall with defects</b>    | 112,518                              | 35,099                               |
| <b>Reference wall sandblasted</b>     | 62,730                               | 48,688                               |
| <b>Reference flat top</b>             | 15,789                               | 6,029                                |

Source: Own authorship.

## **4.8 Remelting Results**

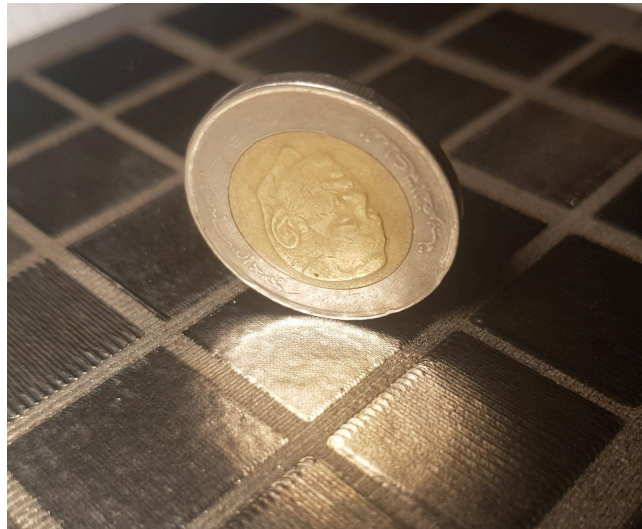
Visual inspection of the remelted testing fields revealed various aspects, including burnt areas where welding soot was visible and other fields that exhibited a certain level of shininess. Figure 38 shows an image of the flat top plate with the first 36 parameter remelted testing fields, while figure 39 illustrates the reflection of a coin on a testing field, demonstrating the shininess obtained after the remelting.

**Figure 38 - Flat top with 36 remelted testing fields**



Source: Own authorship.

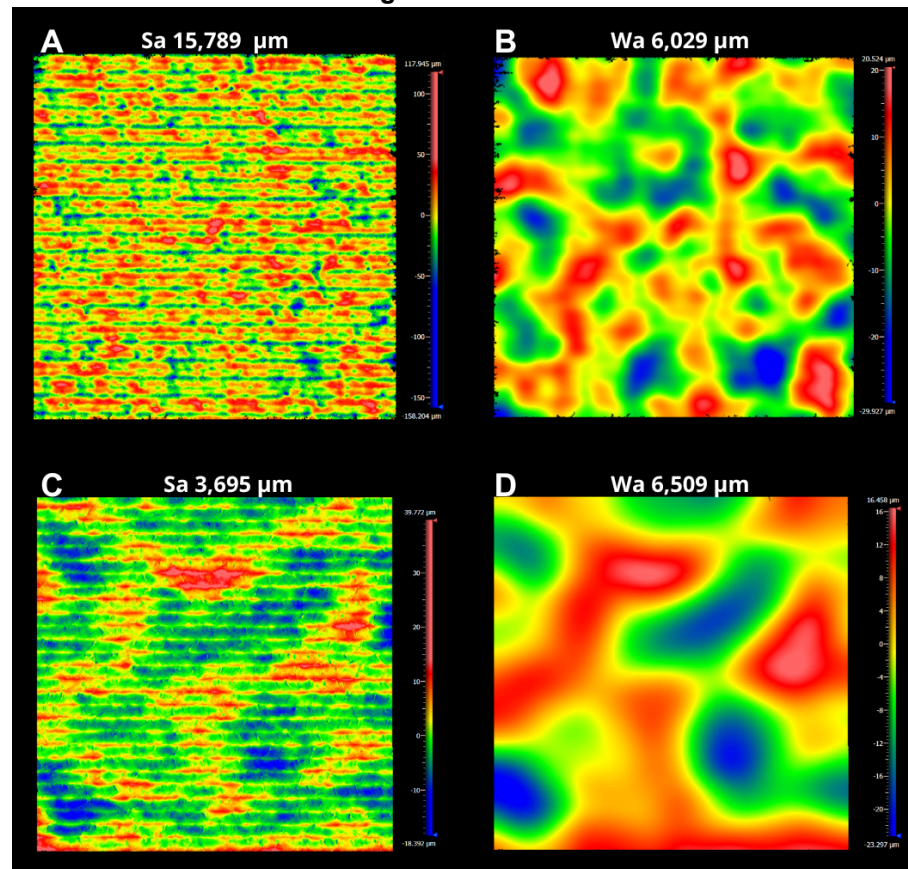
**Figure 39 - Reflection of a Coin demonstrating shininess obtained after the remelting**



Source: Own authorship.

Figure 40 illustrates an example of the resulting image from the measurement and comparison between the reference flat top and the remelted testing field number 28 after the filters were applied.

**Figure 40 - Result image of the WIM measurement for  $Sa$  and  $Wa$  where: A)  $Sa$  Reference flat top B)  $Wa$  Reference flat top C)  $Sa$  flat top remelting test field number 28 D)  $Wa$  flat top remelting test field number 28**

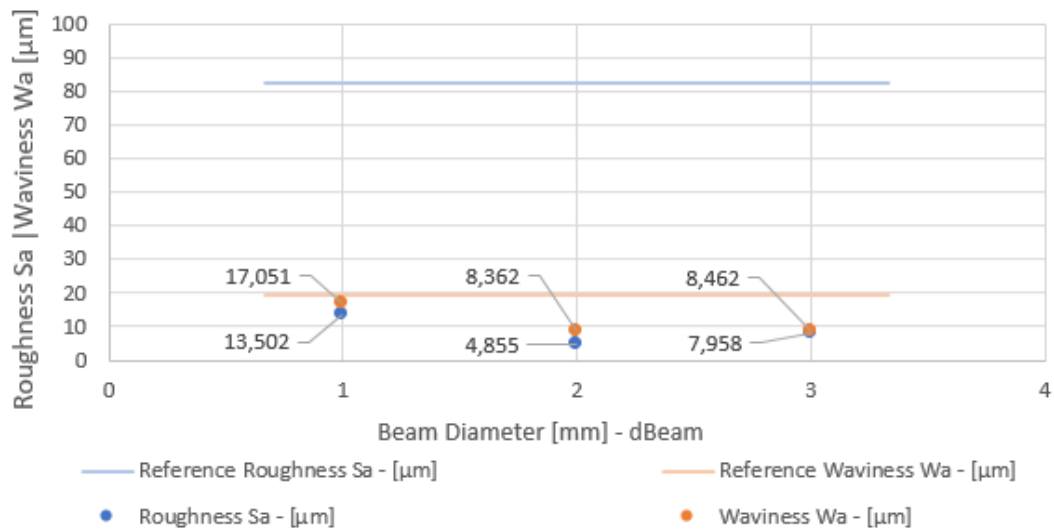


Source: Own authorship.

#### 4.8.1 Laser Beam Diameter Variation

LSS was varied at 3 different values of 1, 2, and 3 mm simultaneously as beam laser power varied at a range from 500 W to 1700 W, while hatch overlap distance and feed rate were kept constant. The respective parameters for the best values obtained for  $Sa$  and  $Wa$  of the remelting fields applied on walls without deposition defects, considering a feed rate of 2 m/min and a hatch overlap distance of 80%, can be verified in figure 41.

**Figure 41 - 1, 2, 3 mm beam Comparison at 2 m/min and 80% overlap hatch distance applied on walls without deposition defects where laser power of 500, 1700 and 1700 W were applied respectively**

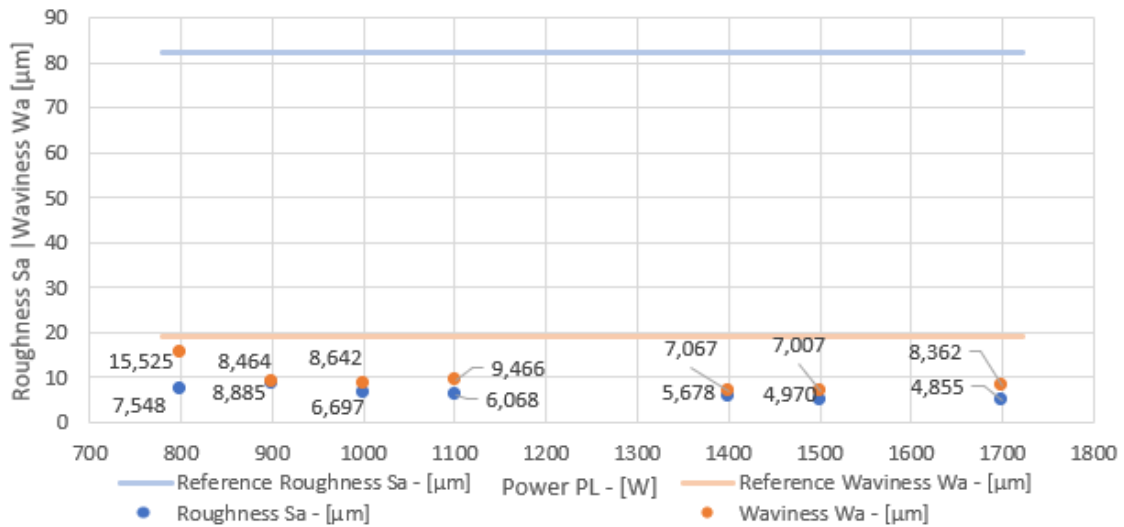


Source: Own authorship.

The graph shows that LSS = 2 mm demonstrated to deliver the best results regarding both variables, roughness and waviness, at this feed rate and hatch overlap distance setup. A beam diameter of 1 mm presented a burnt appearance and soot originated from the remelting process. This LSS also showed its best result for  $Sa = 10,945 \mu\text{m}$  and  $Wa = 15,800 \mu\text{m}$  when applied at a higher feed rate of 5 m/min.

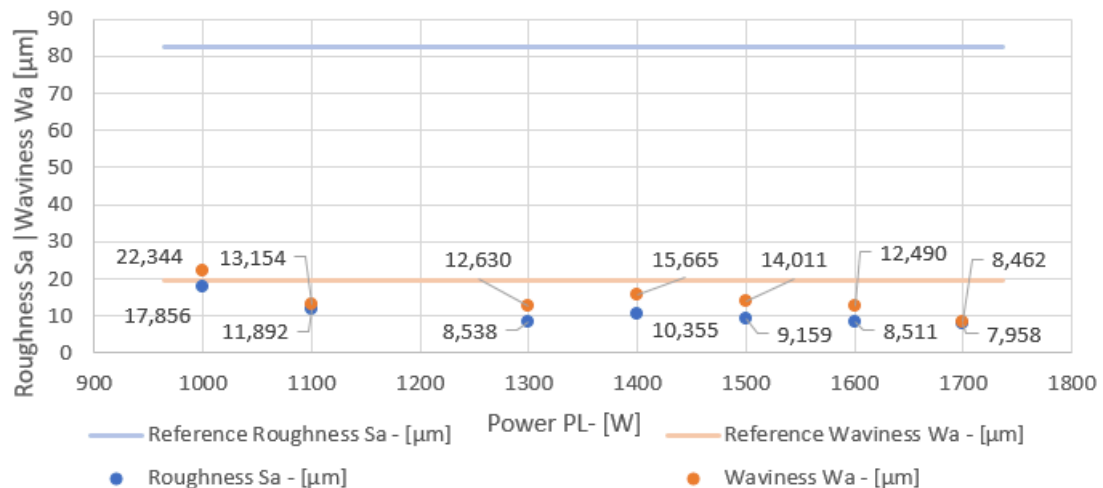
Variating beam diameter between 2 and 3 mm and the laser beam power while keeping the feed rate constant at 2 m/min and hatch overlap distance at 80% shows that remelting testing field that used a LSS = 3 mm presents higher values for  $Sa$  and  $Wa$  when compared to remelted areas done with LSS = 2 mm. When using a LSS = 2, the power range that presents the best values of  $Sa$  and  $Wa$  combined is between 1400 W and 1500 W. The same analysis for LSS = 3 mm can be obtained at the beam laser power of 1600 W. The results analysis also show that  $Sa$  and  $Wa$  decrease as laser beam power increases, getting to a saturation point where  $Sa$  and  $Wa$  values are kept stable. Figure 42 presents the graph with the  $Sa$  and  $Wa$  results when using a 2 mm beam diameter while figure 43 presents the same results when using a 3 mm beam diameter.

**Figure 42 - Power variation at 2 m/min, 80% overlap hatch and 2 mm beam diameter applied on walls without deposition defects**



Source: Own authorship.

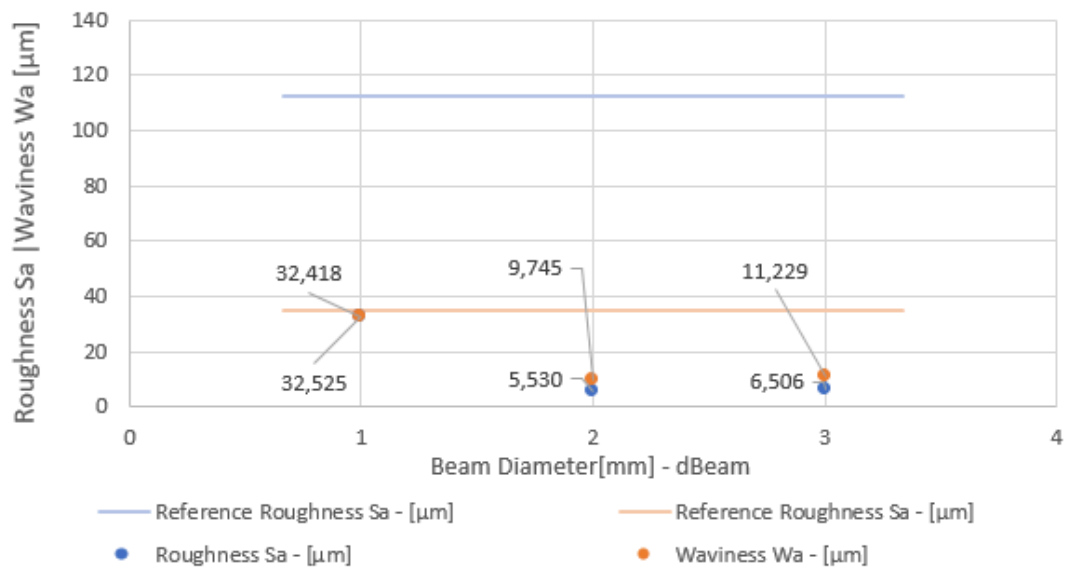
**Figure 43 - Power variation at 2 m/min, 80% overlap hatch and 3 mm beam diameter applied on walls without deposition defects**



Source: Own authorship.

The same analysis presented above regarding the walls with very few deposition defects were also applied to the remelting testing fields used on walls with deposition defects. The results are similar because the remelting parameters applied on the walls without deposition defects are the same parameters applied on the walls with deposition defects. Figure 44 shows the comparison of the beam diameter variation, considering the same parameters applied on the walls with very few deposition defects.

**Figure 44 - 1, 2, 3 mm beam Comparison at 2 m/min and 80% overlap hatch distance applied on walls with deposition defects where laser power of 500, 1700 and 1700 W were applied respectively**

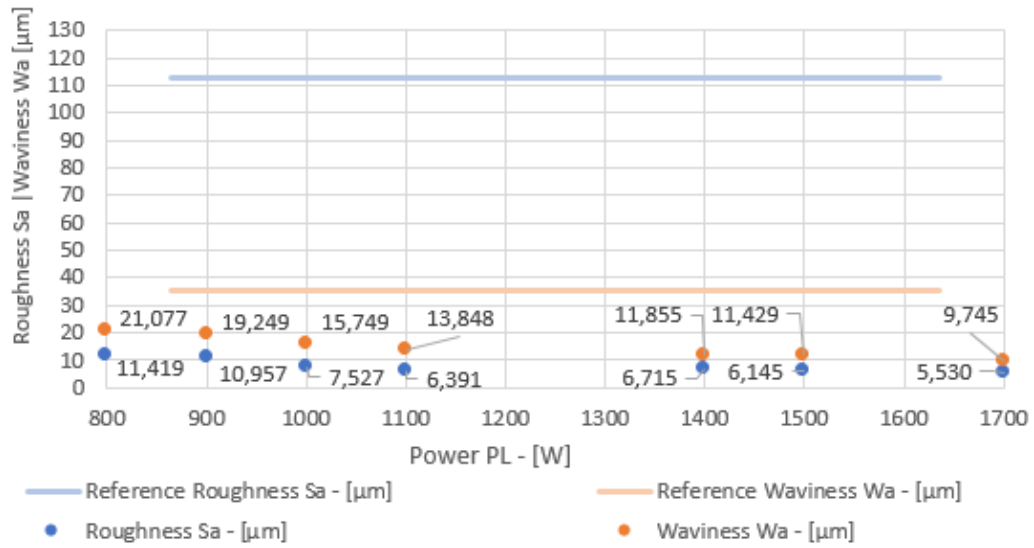


Source: Own authorship.

Comparison between the results from the walls without deposition defects and the wall with deposition defects demonstrates the same pattern when varying beam diameter. Results obtained with a 3 mm beam diameter applied on the walls with deposition defects have the same pattern, however,  $Sa$  values are slightly better in some specific laser power sets when compared to the same results obtained from the remelting applied on walls without deposition defects, while  $Wa$  values are higher due to the deposition defects existent before the remelting application. Figure 45 and 46 show the results for the 2 and 3 mm LSS comparison.

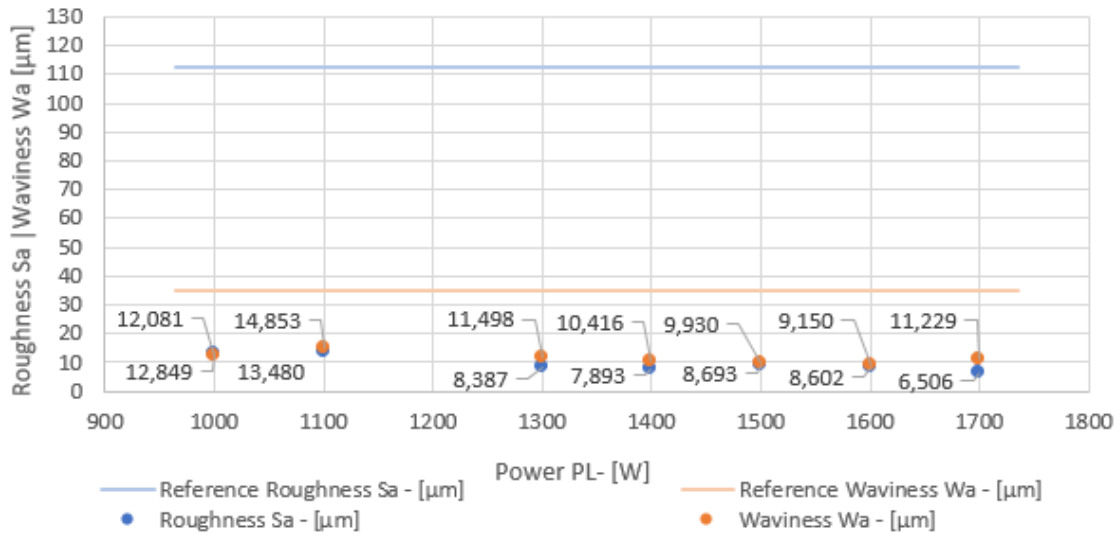


**Figure 45 - Power variation at 2 m/min, 80% overlap hatch, and 2 mm beam diameter applied on walls with deposition defects**



Source: Own authorship.

**Figure 46 - Power variation at 2 m/min, 80% overlap hatch and 3 mm beam diameter applied on walls with deposition defects**

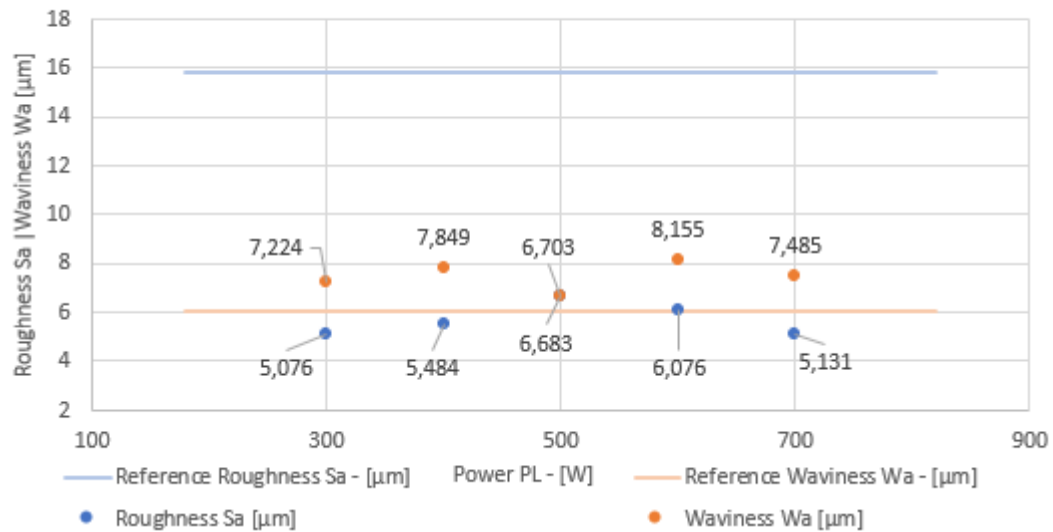


Source: Own authorship.

The findings from remelting experiments on flat top surfaces, concerning the variation in each beam diameter, are outlined below. In this study, beam diameters ranged between LSS = 1 mm, LSS = 2 mm, and LSS = 3 mm, while maintaining a consistent feed rate of 5 m/min and an overlap distance of 80% for each beam diameter. Laser power was adjusted according to each beam parameter. For beam diameters of 1 and 2 mm, similar results were observed for  $S_a$ , whereas

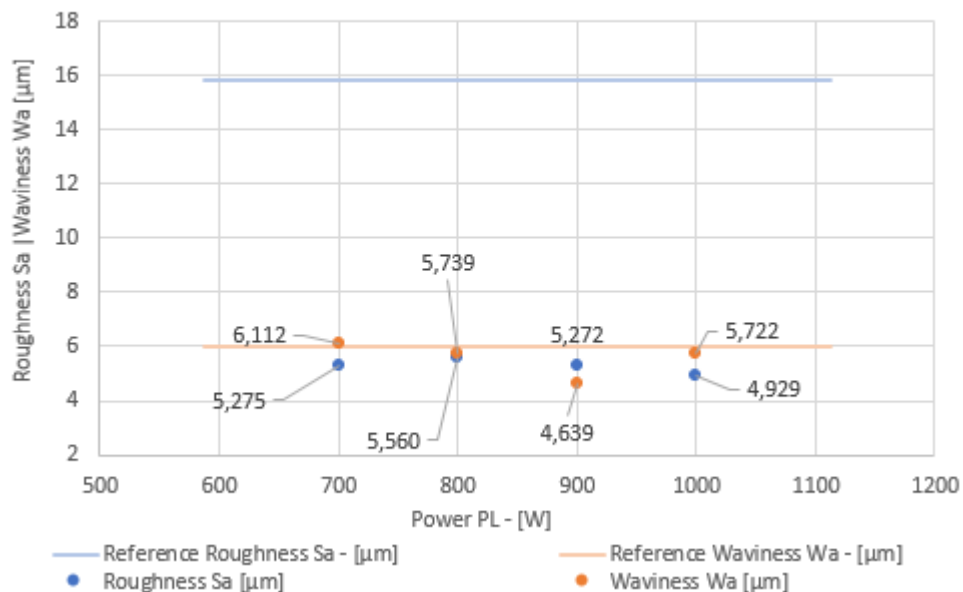
LSS = 2 mm yielded lower values for  $W_a$ . Due to a higher energy density with smaller beam diameters less beam power is required for the remelting process. Employing an LSS = 3 mm also demonstrated higher  $S_a$  than  $W_a$  values, with the difference between these variables widening as laser power increases. Figures 47, 48 and 49 show the comparison between different beam diameters as laser power variates and feed rate and overlap hatch are kept constant.

**Figure 47 - 1 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops**



Source: Own authorship.

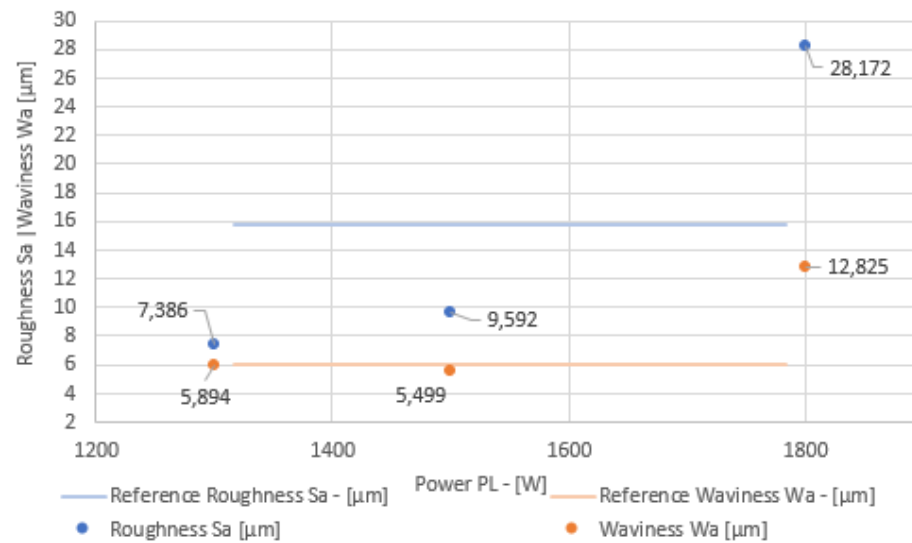
**Figure 48 - 2 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops**



Source: Own authorship.



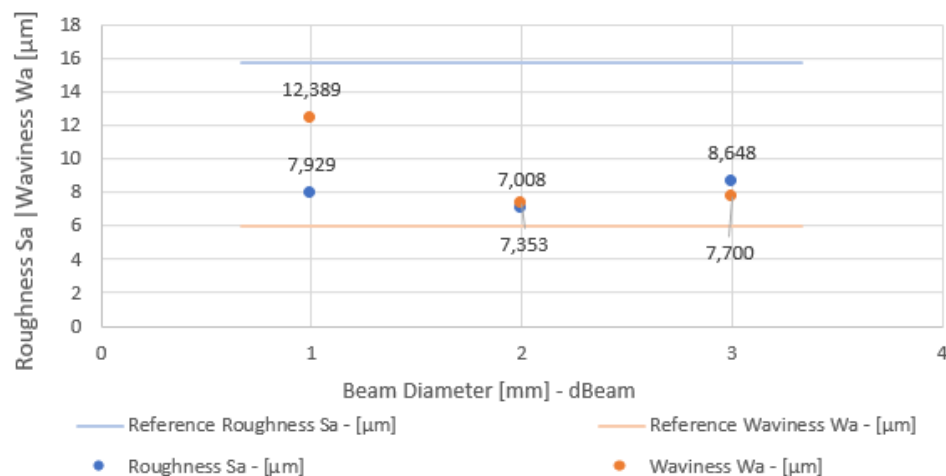
**Figure 49 - 3 mm beam diameter comparison at 5 m/min, 80% overlap hatch and laser power variation applied on flat tops**



Source: Own authorship.

Using a very high feed rate for the remelting of the flat top surfaces demonstrated to have similar results in comparison to slower feed rates. LSS was varied at 3 different values of 1, 2, and 3 mm simultaneously as beam laser power varied at a range from 1300 W to 2700 W, while hatch overlap distance and feed rate were kept constant at 80% and 30 m/min respectively. The parameters for the best values obtained for  $Sa$  and  $Wa$  of the remelting fields applied on flat top depositions can be verified in figure 50, and beam diameter presented the best results in comparison to 1 mm and 3 mm LSS.

**Figure 50 - 1, 2, 3 mm beam comparison at 30 m/min and 80% overlap hatch applied on flat top surfaces where laser power of 1300, 1800 and 2300 W were applied respectively**



Source: Own authorship.

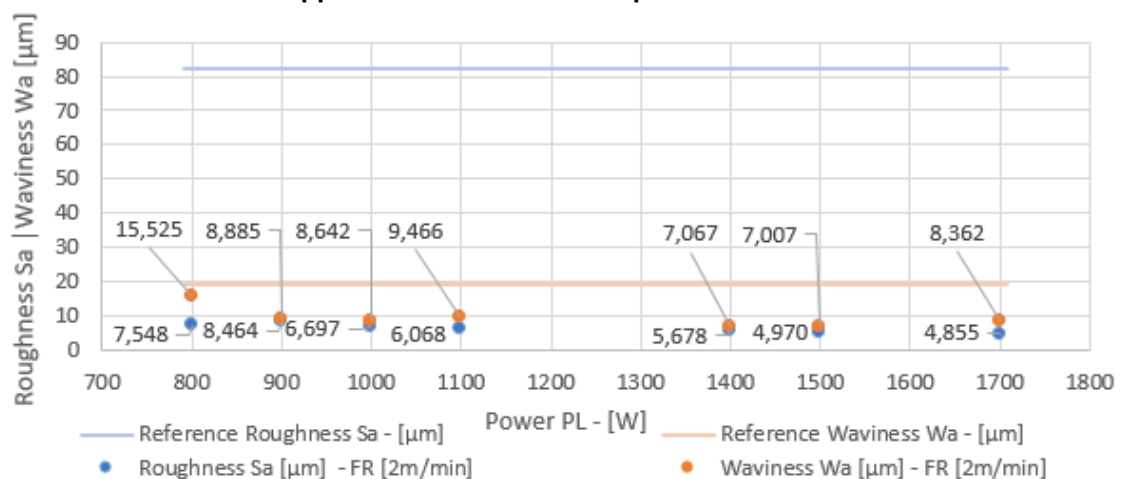
#### 4.8.2 Feed Rate Variation

Feed rate variations applied to the remelting of the surface walls only varied between two values: 2 m/min and 5 m/min. Other feed rates were tested solely on these types of surfaces during stage 2 of the DOE but did not yield promising results, exhibiting insufficient remelting of the testing field.

The following analysis was based on the results from the remelting testing fields applied on surfaces of walls without deposition defects. Maintaining constant values for overlap hatch distance at 80% and beam diameter at 2 mm revealed that a slower feed rate of 2 m/min exhibited lower values for  $Sa$  and  $Wa$ . A saturation point was observed at 1100 W for the feed rate of 2 m/min, as the values showed no significant improvement in laser power variations beyond that point. Additionally, it was noted that a feed rate of 2 m/min could be used with a lower range for laser beam power when compared to a feed rate of 5 m/min.

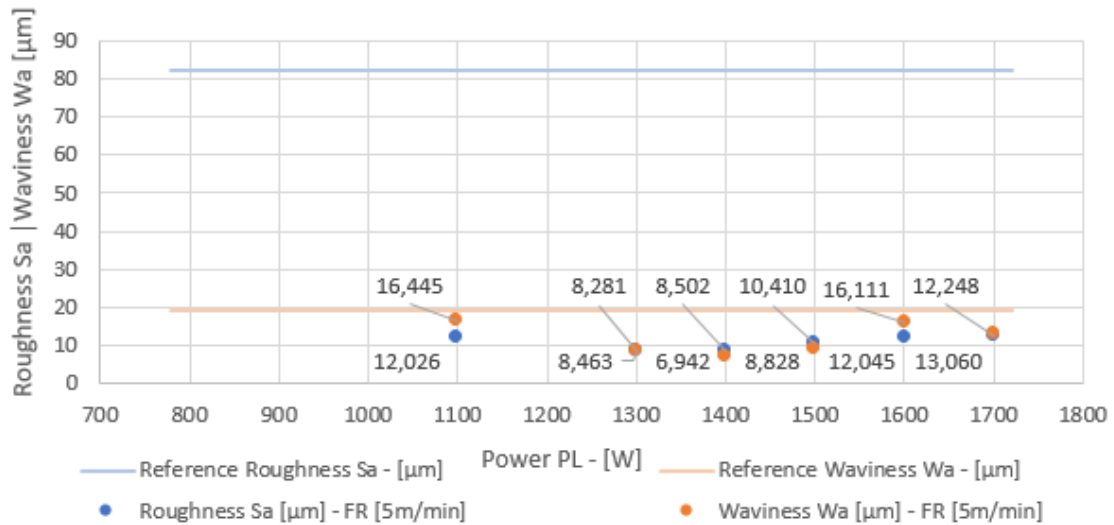
A feed rate of 5 m/min presented higher values of  $Sa$  than  $Wa$  at 1400 W and 1500 W. The feed rate of 5 m/min demonstrated its best results at 1300 W and 1400 W of laser power. Figures 51 and 52 illustrate the graphic representation of the comparison between the two different feed rates detailed above.

**Figure 51 - 2 m/min at 80% overlap hatch, 2 mm beam diameter, and laser power variation applied on walls without deposition defects**



Source: Own authorship.

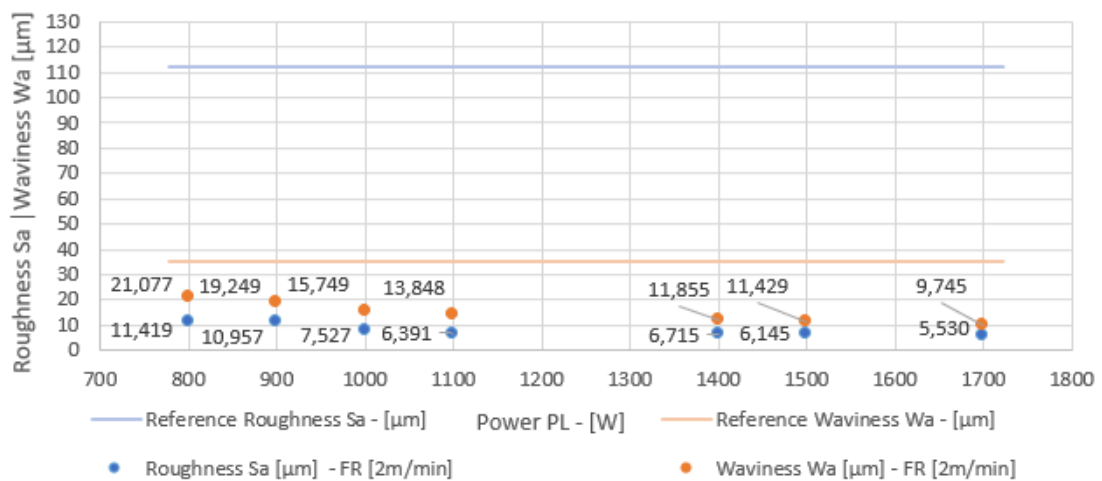
**Figure 52 - 5 m/min at 80% overlap hatch, 2 mm beam diameter, and laser power variation applied on walls without deposition defects**



Source: Own authorship.

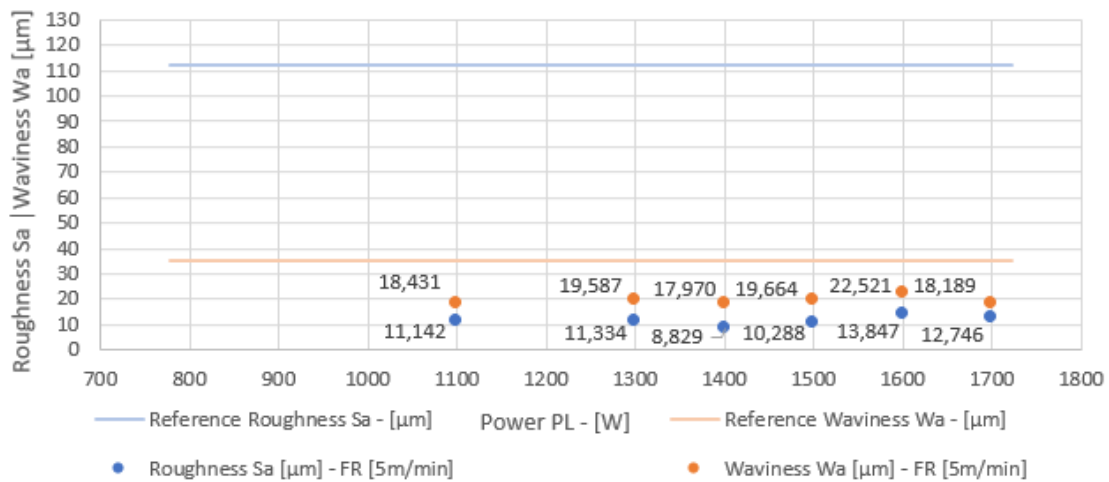
Investigating the same parameters using the same methodology as above and applied to analyze the remelting on the wall with deposition defects, the results are very similar. It is expected that  $W_a$  values from these walls with deposition defects are higher than the results of the walls without deposition defects. Figures 53 and 54 illustrate the graphic comparison of  $S_a$  and  $W_a$  values at different feed rates of 2 m/min and 5 m/min, while laser power varies and hatch distance is kept constant at 80%, along with the beam diameter locked at 2 mm.

**Figure 53 - 2 m/min at 80% overlap hatch, 2 mm beam diameter and laser power variation applied on walls with deposition defects**



Source: Own authorship.

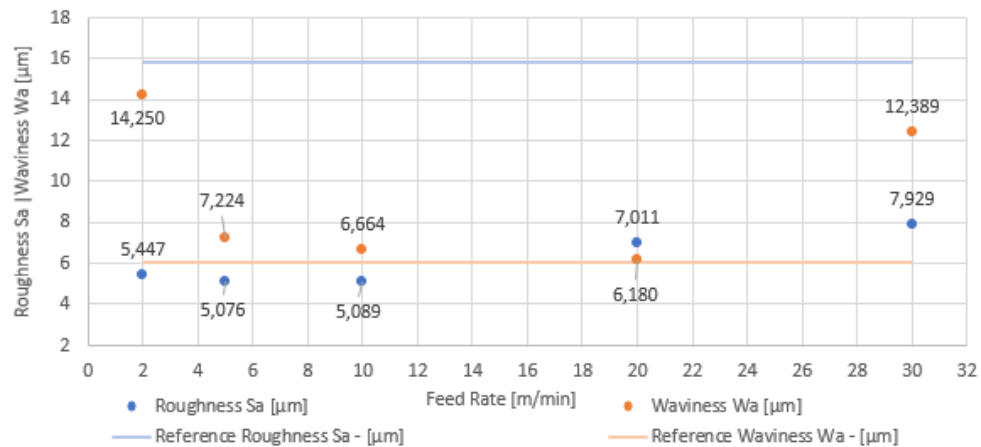
**Figure 54 - 5 m/min at 80% overlap hatch, 2 mm beam diameter and laser power variation applied on walls with deposition defects**



Source: Own authorship.

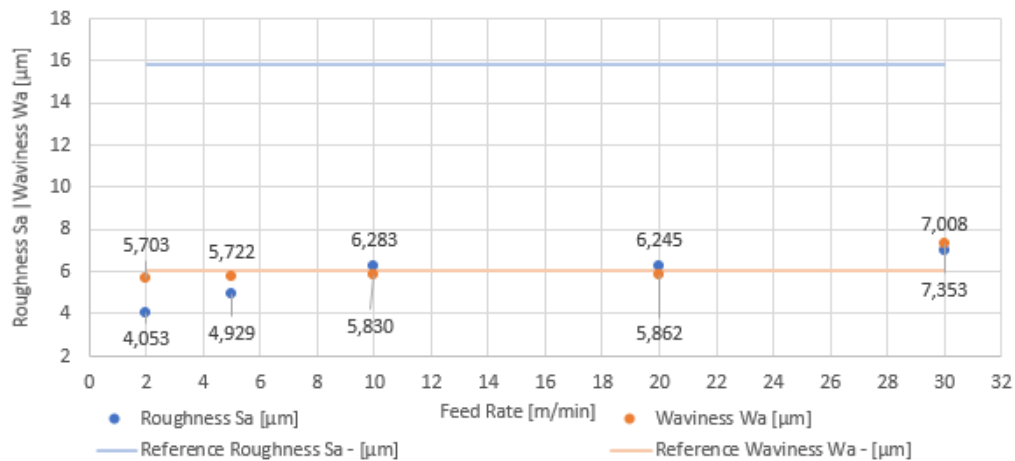
The analysis of the results submitted below examines the effectiveness of the flat top remelting process, considering an 80% overlap between passes. The parameters investigated below encompass the influence of different beam diameters of 1, 2 and 3 mm, and varying feed rate velocities. At a feed rate of 2 m/min and 5 m/min, a tendency of the 1 mm beam to generate higher values of roughness  $Sa$  and waviness  $Wa$ , in contrast to the 2 mm beam, is observed. At 10 m/min, all beam diameters exhibit superior similar performance results. In the case of the 2 mm beam diameter, at 10 m/min, the values of  $Sa$  and  $Wa$  demonstrate saturation observable from 1600 W onwards, indicating a progression towards greater roughness. At a velocity of 20 m/min, the 2 and 3 mm beam diameters exhibited comparable behaviors, although the 2 mm beam diameter presents a more pronounced waviness  $Wa$ . The application of the 30 m/min feed rate demonstrated lower performance and presented higher values for  $Sa$  and  $Wa$ . At 30 m/min, the discrepancy between the values of  $Sa$  and  $Wa$  is noted for beam diameter of 1 mm, while bead diameter of 2 mm presented the best values for  $Sa$  and  $Wa$  at this feed rate. These analyses can be correlated with the visual representations provided in figure 55, 56 and 57.

**Figure 55 - Feed rate variation applied on the flat top at 80% overlap hatch and 1 mm beam diameter where laser power of 500, 300, 800, 1100 and 1300 W were applied respectively**



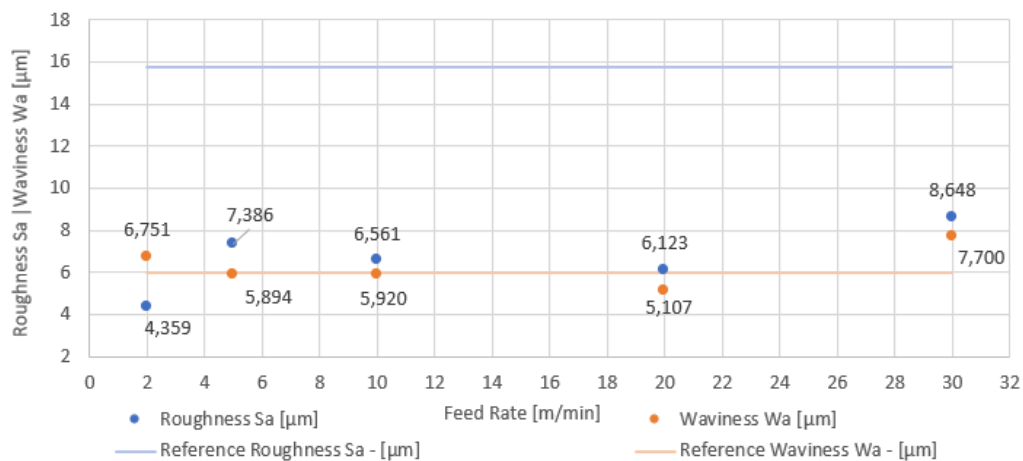
Source: Own authorship.

**Figure 56 - Feed rate variation applied on the flat top at 80% overlap hatch and 2 mm beam diameter where laser power of 700, 1000, 1600, 2100 and 1800 W were applied respectively**



Source: Own authorship.

**Figure 57 - Feed rate variation applied on the flat top at 80% overlap hatch and 3 mm beam diameter where laser power of 1100, 1300, 1500, 1800 and 2300 W were applied respectively**



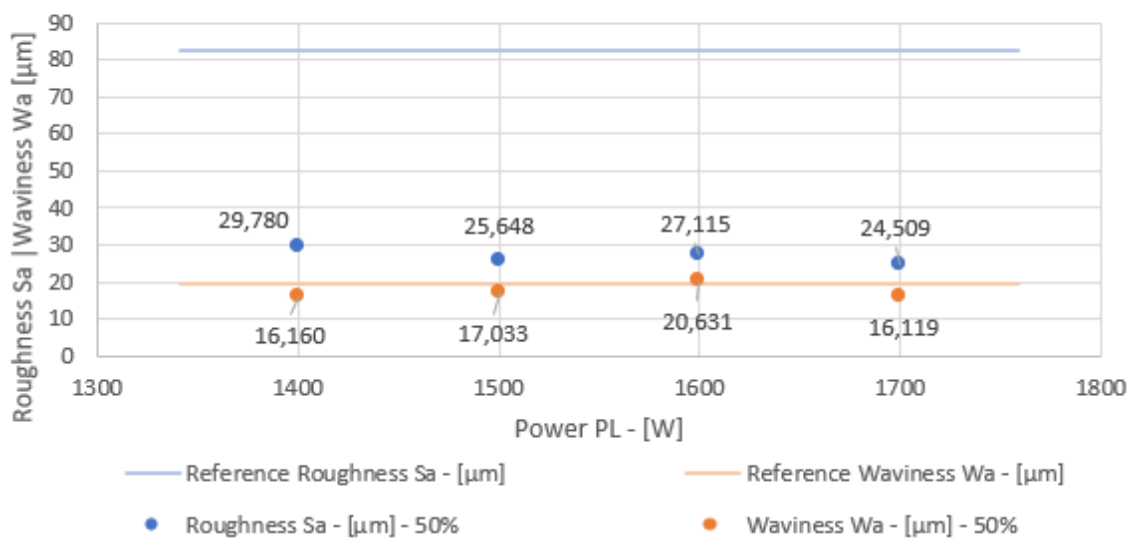
Source: Own authorship.

### 4.8.3 Hatch Overlap Distance

The following analysis was based on the results from the remelting testing fields applied on surfaces of walls without deposition defects. Variations in hatch overlap distance were tested at 50% and 80% values. A 30% overlap was insufficient to achieve complete fusion, as was a 50% overlap when applied to beams with diameters of 1 mm and 2 mm.

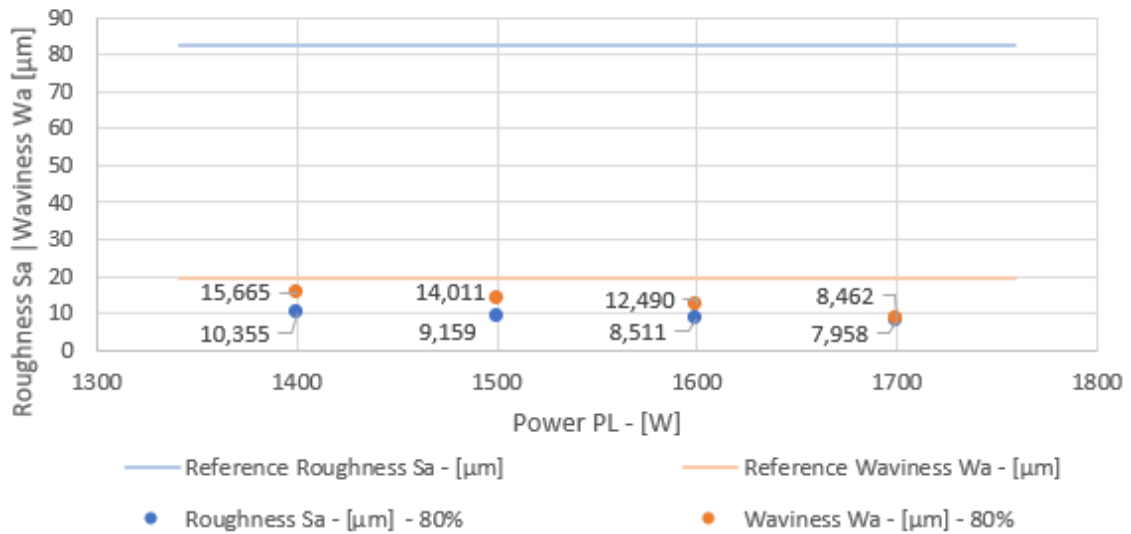
Maintaining a constant feed rate velocity of 2 m/min and a beam diameter of 3 mm allows for a comparison of the impacts of varying hatch overlap distance at 50% and 80% overlap. For an 80% overlap, roughness values  $Sa$  and waviness  $Wa$  are lower across all power variations compared to the 50% overlap. Results indicate that  $Sa$  values are higher than  $Wa$  values when a 50% overlap is applied. These comparisons are illustrated in Figures 58 and 59 below.

**Figure 58 - 50% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power**



Source: Own authorship.

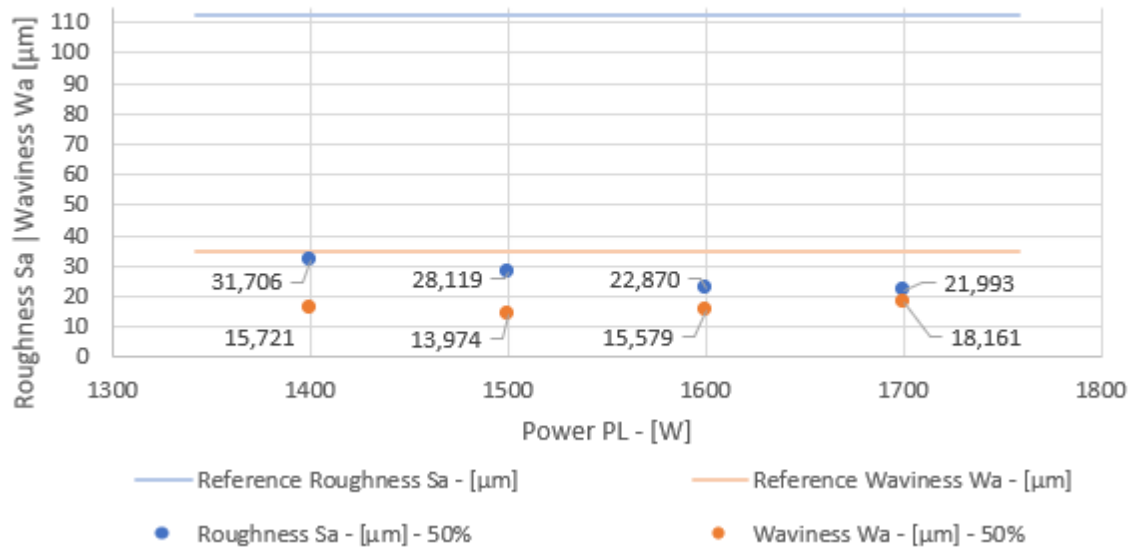
**Figure 59 - 80% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power**



Source: Own authorship.

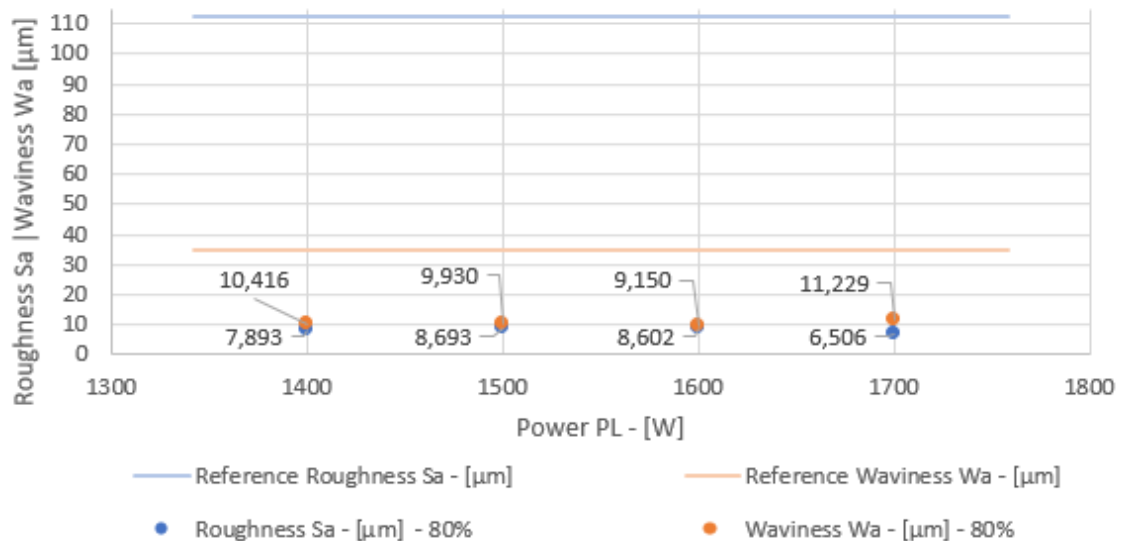
The results obtained from the application of remelting on surfaces of walls with deposition defects are presented below. Comparisons between 50% and 80% overlap variations were conducted at a constant feed rate velocity of 2 m/min and a beam diameter of 3 mm. The outcomes mirror those observed in the remelting of surfaces of walls without deposition defects, except for lower values of roughness  $Sa$  and waviness  $Wa$  when employing an 80% overlap. At 50% overlap hatch,  $Sa$  values decrease gradually as laser power increases, while  $Wa$  values increase with power escalation, except for laser power of 1400 W, which has a similar value as laser power of 1600 W. Figures 60 and 61 illustrate the comparison graph between 50% and 80% overlap of remelting applied on the surface of walls with deposition defects.

**Figure 60 - 50% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls with deposition defects while varying laser power**



Source: Own authorship.

**Figure 61 - 80% overlap hatch comparison at 2 m/min and 3 mm beam diameter applied on walls without deposition defects while varying laser power**



Source: Own authorship.

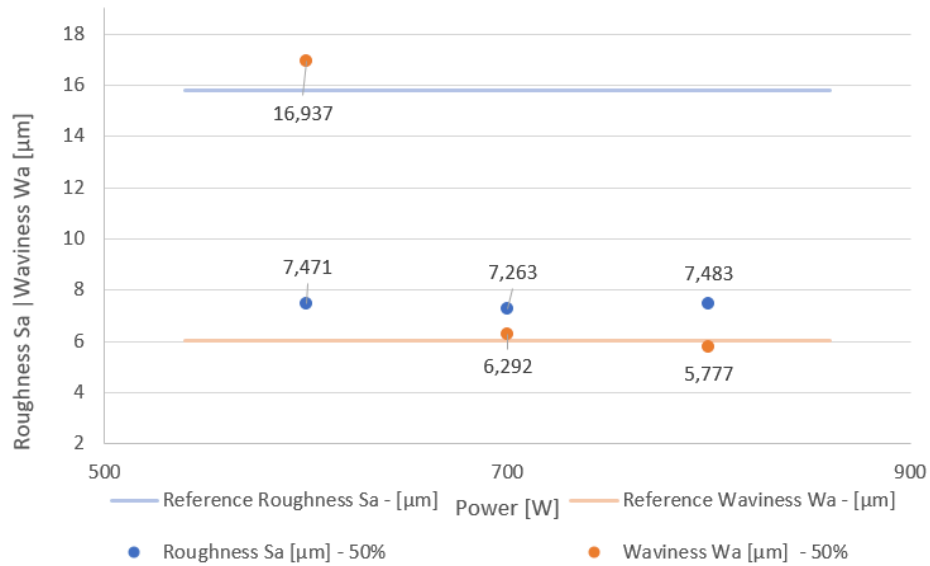
The analysis of results obtained from remelting surfaces with flat top characteristics included a comparison between variations of 50% and 80% overlap. This comparison was conducted at a consistent feed rate velocity of 5 m/min and a constant beam diameter of 1 mm.

In cases of the 80% overlap hatch, both roughness  $Sa$  and waviness  $Wa$  values exhibited a decrease as laser power increased. Conversely, with the 50%



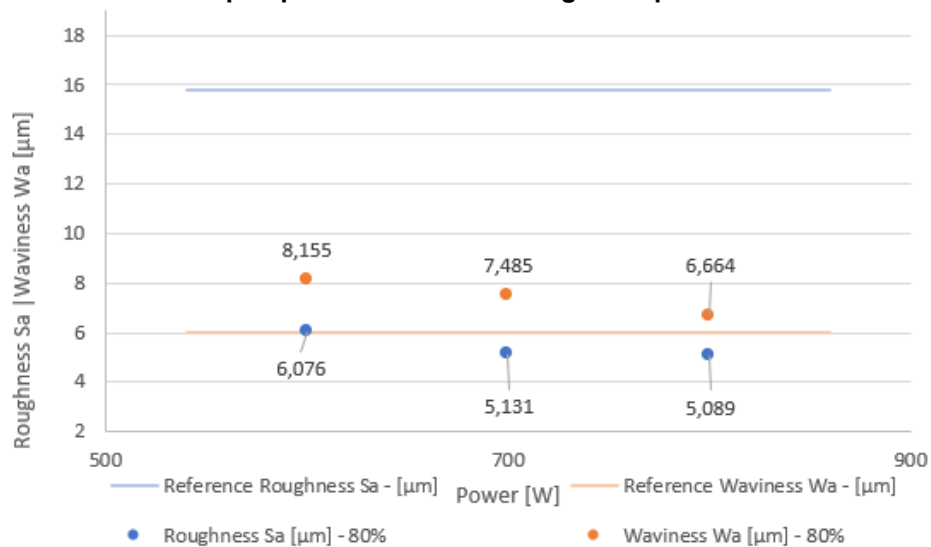
overlap,  $Sa$  values surpassed  $Wa$  values as laser power increased, except at 600 W where  $Wa$  remained higher than  $Sa$  value. Figures 62 and 63 illustrate the graphical comparison between the 50% and 80% overlap distances in the remelting of flat top surfaces.

**Figure 62 - 50% overlap hatch comparison at 5 m/min and 1 mm beam diameter applied on flat top deposition while varying laser power**



Source: Own authorship.

**Figure 63 - 80% overlap hatch comparison at 5 m/min and 1 mm beam diameter applied on flat top deposition while varying laser power**

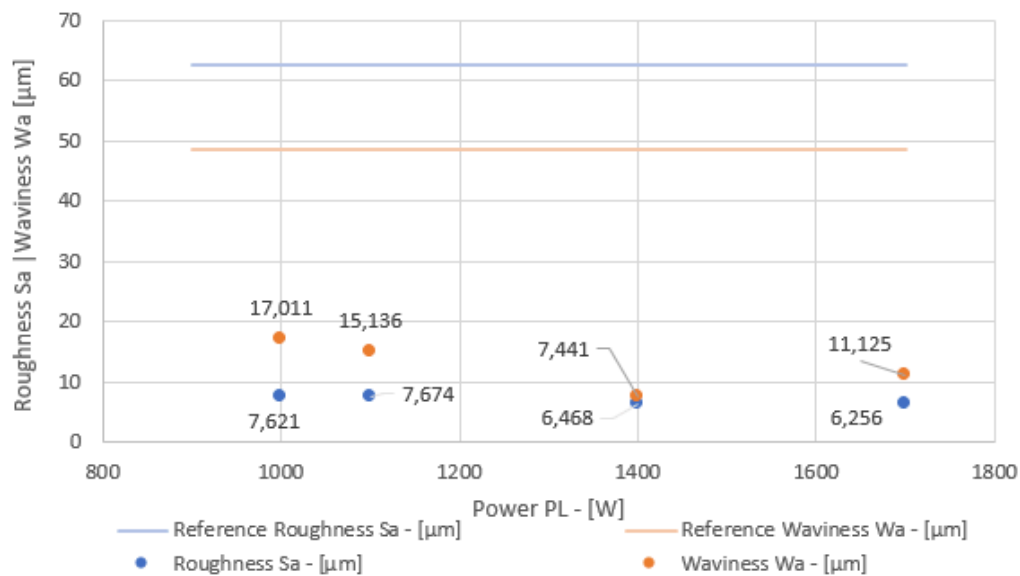


Source: Own authorship.

#### 4.8.4 Sandblasted walls

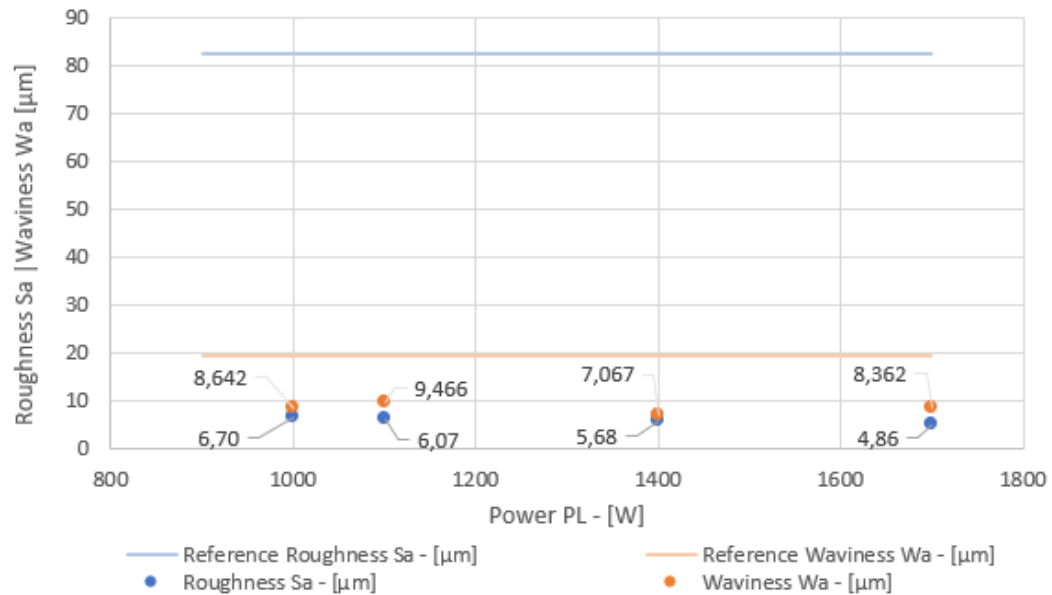
Comparison of results between remelting applied to walls subjected to sandblasting and walls that were not sandblasted before the remelting application demonstrates a certain repeatability of the remelting process, as the same parameters were applied to both surfaces and yielded a similar pattern of results. This comparison considered the best  $Sa$  and  $Wa$  results obtained in remelting walls with sandblasting, compared to the results obtained in walls without sandblasting that had the same parameters applied. At a constant feed rate velocity of 2 m/min, 80% overlap hatch, and beam diameter of 2 mm, with the same power variation, lower  $Sa$  and  $Wa$  values were observed for remelting applied to walls without sandblasting compared to walls with sandblasting. A greater amplitude between  $Sa$  and  $Wa$  values were observed in walls with sandblasting. Figures 64 and 65 displays the diagram representing the previously mentioned comparison.

**Figure 64 - Results of  $Sa$  and  $Wa$  values from the sandblasted wall at a feed rate of 2 m/min, beams diameter of 2 mm and 80% overlap hatch while varying laser power**



Source: Own authorship.

**Figure 65 - Results of  $Sa$  and  $Wa$  values from the non-sandblasted wall at a feed rate of 2 m/min, beams diameter of 2 mm and 80% overlap hatch while varying laser power**

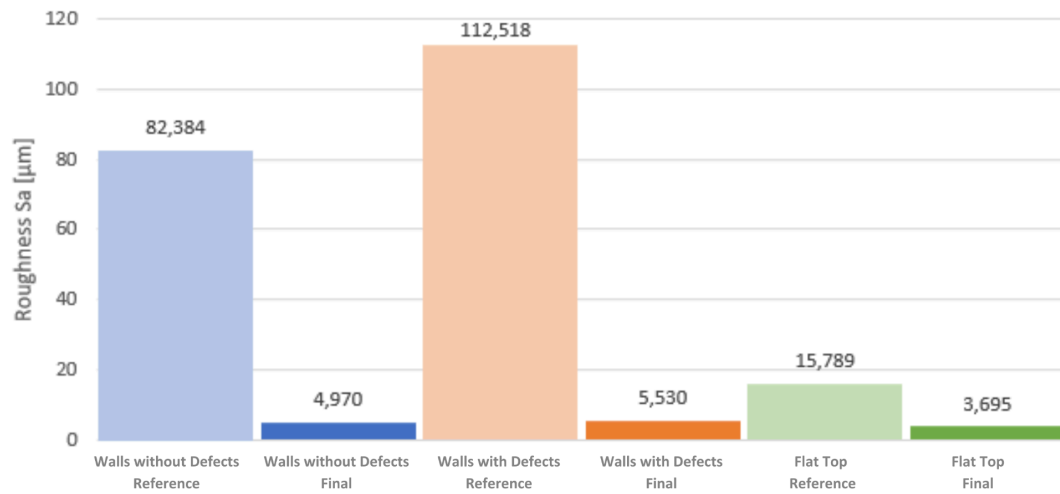


Source: Own authorship.

#### 4.9 Remelting Results Overview

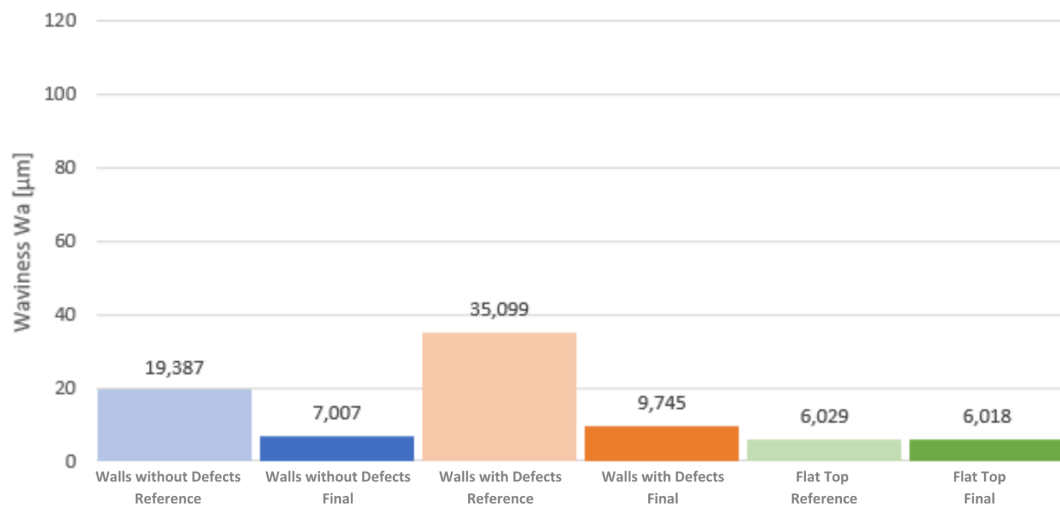
In comparison with the initial roughness values measured after the construction of the walls, the best results show an improvement of up to 93,97% on the surfaces of the walls without deposition defects and an improvement of up to 95,08% on the walls that had deposition defects on its surface. On flat-top surfaces, the surface improvement was 76,6% in roughness reduction when compared to the initial measured values. Measurements on the surfaces of the walls after remelting showed an improvement of up to 63,86% on the walls without deposition defects and an improvement of up to 72,24% on the walls with deposition defects regarding waviness when compared to the initial measurement. Waviness measurements on the flat top after remelting showed that the final value remained very close to the initial one, which did not bring significant improvement in this variable. Figures 66 and 67 show the graphic representation of the improvement obtained in this study.

**Figure 66 - Comparison between initial and final  $S_a$  values for walls without deposition defects, walls with deposition defects, and flat top depositions**



Source: Own authorship.

**Figure 67 - Comparison between initial and final  $W_a$  values for walls without deposition defects, walls with deposition defects, and flat top depositions**



Source: Own authorship.

Table 14 presents the remelting parameters used for the comparison of the graphic representations above, illustrating the best results achieved in this study.

**Table 14 - Remelting parameters used in the comparison between reference and best results achieved for  $S_a$  and  $W_a$**

| <b>Probe</b>                    | <b>Beam diameter [mm]</b> | <b>Feed rate [m/min]</b> | <b>Hatch distance [%]</b> | <b>Laser power [W]</b> | <b><math>S_a</math> [<math>\mu\text{m}</math>]</b> | <b><math>W_a</math> [<math>\mu\text{m}</math>]</b> |
|---------------------------------|---------------------------|--------------------------|---------------------------|------------------------|----------------------------------------------------|----------------------------------------------------|
| Walls without deposition defect | 2                         | 2                        | 80                        | 1500                   | 4,970                                              | 7,007                                              |
| Walls with deposition defect    | 2                         | 2                        | 80                        | 1700                   | 5,530                                              | 9,745                                              |
| Flat top                        | 2                         | 2                        | 80                        | 600                    | 3,695                                              | 6,018                                              |

Source: Own authorship.

## 5 FINAL CONSIDERATIONS

The present study demonstrates the feasibility of producing objects with high efficiency using the EHLA3D deposition method, achieving geometric dimensions very close to those programmed for deposition. Stainless steel 316L blocks constructed by this method exhibit dimensional loss on the sides as the object grows along the z-axis. To obtain a specific dimension piece through the EHLA3D process in its current configuration, it is necessary to consider this dimensional loss on the sides, ensuring the final piece meets the specified dimensions in the design. The use of the linear hatching with one extra welding bead deposition strategy proved highly effective in maintaining wall thickness compared to what was programmed, although this may result in deposition defects due to material buildup on the lateral surface of the wall. Further studies on the EHLA3D process regarding parameter development combined with deposition strategies, and even the use of a laser source with top hat energy density distribution, can contribute to process optimization and consequently build objects with greater geometric precision.

The development of the design of experiments was an important step in the practical experiment elaboration, allowing for the organization and crossing of different possible parameter combinations to extract the most from the experimental tests.

Results achieved by the remelting process were satisfactory considering the reduction in roughness and waviness of remelted surfaces. The study compared the application of 30 different combinations of parameters on two walls with similar surface characteristics, but one contained deposition defects which, according to topographic measurements in the WIM, exhibited higher waviness than the surface of the wall without deposition defects. The comparison revealed that the initial finishing quality of the object to be remelted directly influences the results, with initially more wavy surfaces (with deposition defects) even after remelting showing higher waviness compared to similar surfaces without initial deposition defects.

The study also compared the application of a selection of 10 parameters applied to wall surfaces, which were applied to a wall surface that had undergone a

sandblast step before remelting. It was believed that the removal of oxidation resulting from the laser deposition process would bring better surface finish results, which, according to the tests conducted, did not prove true. In this case, it is not an attractive option for an industrial procedure since the extra step added to the process flow did not bring a significant contribution to justify its use.

Remelting applied to surfaces with flat top characteristics showed a significant improvement in surface roughness while waviness remained practically stable. The highlight of the remelting applied to the flat top lies in the high feed rates that can be achieved, as the initial surface has a lower roughness value compared to the initial roughness on the surface of the walls.

In comparison with the initial roughness values, the best result shows an improvement of up to 95.08% for wall surfaces that had remelting applied after their construction by EHLA3D. On flat top surfaces, the surface improvement was 76.6% in roughness reduction. Measurements on surfaces of the wall after remelting showed an improvement of up to 72.24% in waviness compared to the initial measurement. Waviness measurements on the flat top after remelting showed that the final value remained very close to the initial one, which did not bring significant improvement in this variable.

In conclusion, the surface remelting technique investigated in this study holds the potential to enhance object surfaces fabricated through EHLA3D technology, ensuring compliance with roughness and waviness criteria within process limitations in an industrial production line. This approach optimizes process efficiency by taking advantage of the high feed rates that can be achieved during deposition and remelting, thereby streamlining manufacturing, and finishing workflows. Furthermore, its incorporation into the same machinery responsible for manufacturing the objects leads to a reduction in the overall manufacturing duration, aligning with the industry's trajectory towards sustainable development, without compromising the cost-benefit ratio.

## 5.1 Suggestions for Future Research

Additional research avenues could focus on enhancing both the deposition and remelting processes. Parameter optimization for the deposition process, encompassing deposition strategy and laser configuration adjustments such as transitioning from a Gaussian wave to a top hat energy density distribution, warrants further exploration. Moreover, a comprehensive analysis of the study's findings, including dye penetrant liquid testing, Scanning Electron Microscope (SEM) analysis, and microstructural examination, offers valuable insights for identifying deposition or remelting defects and keeping the material integrity.

Regarding the remelting procedure, future investigations could explore the application of multiple remelting passes within the same area and the implementation of alternating scanning directions. Additionally, future studies could investigate the influence of parameters, such as shielding gas, on the final measurement of surface waviness. Furthermore, research could focus on the possibility of using solid fluxes, such as  $\text{CaF}_2$ , to control surface tensions and, consequently, the final waviness.

Examining the application of identical parameters on different materials with similar characteristics, such as Inconel IN718, could yield valuable insights. Lastly, a proposed experiment for future research involves constructing a 3D object followed by remelting, mimicking real-world scenarios to meet specific geometric and topographic dimensions using EHLA3D deposition followed by laser remelting.



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