

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

Murilo Bloch

**Extreme High-Speed Laser Metal Deposition process: Data acquisition for Quality
Assurance by software solutions**

FLORIANÓPOLIS, 2024

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Final Course Work submitted to the Federal Institute of Education, Science and Technology of Santa Catarina as part of the requirements for obtaining the degree of Mechatronics Engineer in 2024.

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EXTREME HIGH-SPEED LASER METAL DEPOSITION PROCESS: DATA ACQUISITION FOR QUALITY ASSURANCE BY SOFTWARE SOLUTIONS

MURILO BLOCH

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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This monograph is dedicated to my parents,
who have been the pillars of my personal and
intellectual development.

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ABSTRACT

This thesis focuses on the developing and enhancement of monitoring tools for the Extreme High-Speed Laser Metal Deposition process (German acronym: Extremes Hochgeschwindigkeits-Laserauftragschweißen, EHLA). Within the realm of Additive Manufacturing (AM) applications, specifically in Laser Metal Deposition (LMD), the pursuit of process refinement paves the way for the integration of the EHLA process (FRAUNHOFER, 2012). The technology poses challenges in the efficient collection and interpretation of data due to its high speed compared to the conventional process (up to 100 times faster than LMD). So far, there are few tools and limited capability to monitor the EHLA process. Correlating acquired data with the process outcomes (specifics, inconsistencies in layers, etc) reveals the technology in more detail, preparing it for the industry. In response to this challenge, a software solution is proposed and designed to operate multiple area monitoring cameras, each with a high frame rate, correlating the images with part coordinates by the Computer Numerical Control (CNC) controller. The research aims not only to improve the process, but also to provide meaningful insights into the EHLA process, enhancing the understanding of the complexity and maximizing its potential for industry use.

Keywords: Extreme High-Speed Laser Metal Deposition (EHLA), Laser Metal Deposition (LMD), Additive Manufacturing (AM), Process Monitoring and Data Analysis.

RESUMO

Esta tese concentra-se no desenvolvimento e aprimoramento de ferramentas de análise e monitoramento para o processo de Extreme High-Speed Laser Metal Deposition (Sigla Alemã: Extremes Hochgeschwindigkeits-Laserauftragschweißen, EHLA). No âmbito das aplicações de Manufatura Aditiva (MA), e particularmente na Deposição de Metal a Laser (LMD), a busca pelo refinamento do processo abre caminho para a integração do processo EHLA (FRAUNHOFER, 2012). A tecnologia apresenta desafios na coleta eficiente e interpretação de dados devido à sua alta velocidade em comparação com o processo convencional (até 100 vezes mais rápido do que o LMD). Até o momento, existem poucas ferramentas e uma limitada capacidade para monitorar o processo EHLA, correlacionar os dados adquiridos com os resultados do processo (particularidades, inconstâncias nas camadas, etc.) revela com mais detalhes a tecnologia, preparando-a para a indústria. Em resposta a esse desafio, propõe-se uma solução em software projetada para operar múltiplas câmeras de monitoramento por imagens, cada uma com uma alta taxa de quadros por segundo, correlacionando as fotografias à coordenadas da peça pelo Controle Numérico Computadorizado (CNC). Este trabalho tem por objetivo não só a busca por avanços no processo, mas também produzir insights significativos do processo EHLA, impulsionando a compreensão das complexidades e maximizando seu potencial para a indústria.

Palavras-chave: Deposição de Alta Velocidade de Metal a Laser (EHLA), Deposição de Metal a Laser (LMD), Manufatura Aditiva (MA), Monitoramento de Processos e Análise de Dados.

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LIST OF ABBREVIATIONS AND ACRONYMS

3D	Three-Dimensional
AI	Artificial Intelligence
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
BJ	Binder Jetting
CNC	Computer Numerical Control
DED	Direct Energy Deposition
EHLA	<i>German acronym Extremes Hochgeschwindigkeits-Laserauftragschweißen</i> (Extreme High-Speed Laser Material Deposition)
HAZ	Heat Affected Zone
HMI	Human Machine Interface
IFSC	<i>Federal Institute of Santa Catarina</i> (Instituto Federal de Santa Catarina)
IP	Internet Protocol
LMD	Laser Metal Deposition
MA	Manufatura Aditiva
ME	Material Extrusion
MJ	Material Jetting
PBF	Powder Bed Fusion
R&D	Research and Developing
ROI	Region Of Interest
SDK	Software Development Kit
SL	Sheet Lamination

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1 INTRODUCTION

The process of joining materials has a long history, by the end of the 19th century, the appearance of equipment capable of generating and manipulating electric current facilitated the emergence of resistance welding and arc welding processes. These processes, capable of quickly reaching high temperatures, allowed the generation of a molten pool in the application region, joining the involved parts upon solidification. (WEMAN, 2003)

Additive Manufacturing (AM), or three-dimensional (3D) printing, has been proving its worth and broadening its horizons in the market, improving productivity due to its performance and competitiveness. Printing a piece in metal with a complex geometry, allows the to think more about better integrated products. As the technology is getting more intricate, more challenges and advancements in the process are taking place.(VAFADAR *et al.*, 2021)

In the ever-evolving landscape of manufacturing and materials processing, the introduction of laser technology has been a transformative force. This technological leap gave rise to the LMD process (LISIECKI, 2022) and one of its offshoots, Extreme High-Speed Laser Metal Deposition (EHLA). (SCHOPPHOVEN; GASSER; BACKES, 2017)

In the rapidly evolving landscape of manufacturing and materials processing, the emergence of technologies like EHLA underscores the pressing need for enhanced control and precision (BUSCHMANN *et al.*, 2021). As engineering endeavors strive for efficiency and reliability, there is a critical focus on refining software and mechanisms for capturing data during procedural events (SOORI; AREZOO; DASTRES, 2023). This aligns with the inherent objective of engineering work to optimize processes and outcomes through systematic improvement (PAHL *et al.*, 2007).

In the pursuit of establishing EHLA as a standard industrial application, there arises a necessity for quality assurance. For this reason, this thesis is dedicated to developing software solutions capable of acquiring and analyzing data during process events. Such initiatives not only bolster operational oversight but also contribute to a deeper understanding of the intricacies of the EHLA process.

1.1 Justifications

Technologies that are coming from Additive Manufacturing, such as the Extreme High-Speed Laser Metal Deposition process, carried out many types of applications. Addition of material, such as coating corrosion and wear protection (SCHOPPHOVEN; GASSER; BACKES, 2017). Having better tools for analysing and understanding the process is extremely important for the industry, and also, in the Research and

Developing (R&D) environment, for optimizing data acquisition and processing, in order to establish new metrics for the process.

According to Buschmann *et al.* (2021), the industry demands higher-quality data to refine techniques and improve overall information quality. However, there are few machinery suppliers and technical experts proficient in applying the EHLA process. Multiple tests must be evaluated in a controlled environment to ensure the component is devoid of defects such as pores, cracks, and bonding issues. Manual and individual testing is necessary to develop optimal parameters until achieving the desired structure that meets the established requirements (THIELE *et al.*, 2020).

To enhance the EHLA process for the industry, this thesis aims to improve high-speed image capture rates while synchronizing coordinate acquisition. This facilitates spatial tracking of images in relation to physical objects, enabling the detection of variations in image patterns that may be indicative of process disturbances potentially leading to defects in the manufactured piece.

Other resources, such as microscopy or roughness measurements, help with more in-depth inspection (FREDERIC; VOORT, 2019), making it possible to create a correlation of cause and effect according to each type of material and the corresponding variation.

1.2 Problem Definition

The challenge is the urgent need to develop and improve specific analysis and monitoring tools for the EHLA process. EHLA is a promising technology, characterized by substantially higher process speed compared to the conventional LMD process. This feature results in subtle variations and nuances, posing a significant challenge to human visual inspection alone. Therefore, there is a crucial need to use and manipulate cameras with a high frame rate per second to increase the amount of detail of the information and interrelationships that the images may contain. Improving the process of identifying errors and gaining insights during the EHLA procedure, emerges as an essential strategy. This solution's purpose is to streamline the gap between the industry field and academic field, allowing quality assurance of the EHLA process with detailed data information and characteristics of the process. The manipulation of up to 4 cameras in the software, enables different perspectives of the same moment in the procedure. Additionally, the use of a time stamp to synchronize images and coordinates enables the determination of process deviations' location. This approach promises to be a crucial step in overcoming the challenges inherent in the dynamic and rapid nature of EHLA.

1.3 General Objective

The main objective of this thesis is to develop software in the C++ programming language to integrate the process of capturing and manipulating images with up to 4 industrial cameras, together with data supplied by the CNC controller for the EHLA process. The software enables the capture of images from cameras positioned at different angles throughout the process. Additionally, it records the spatial position of these images relative to the produced part. With the output images, produce further analysis with Python, to evaluate features and correlation with parameters used in the process.

1.4 Specific Objectives

The specific objectives are listed below:

- a) Integrate the communication of the CNC Control Fanuc Series 31i Model B5 with the C++ software through the Focas 2, Software Development Kit (SDK) set of libraries offered by Fanuc
- b) Integrate and configure Basler industrial cameras, with the software to capture and manipulate the images obtained, using the Pylon SDK provided by Basler
- c) Build a Human Machine Interface (HMI) for manipulations in the program
- d) Create a timestamp mechanism to synchronize the data
- e) Validate the precision of the program
- f) Testing parameters for an EHLA process and acquiring test data
- g) Utilize Python to conduct image post-processing and data analysis to extract key parameters such as melt-pool size and circularity, as well as the overall brightness of the image
- h) Identify quality parameters by analysing outputs
- i) Document achieved results.

2 THEORETICAL FOUNDATION

This chapter explores the current state of LMD and EHLA techniques, as well as post-processing methods.

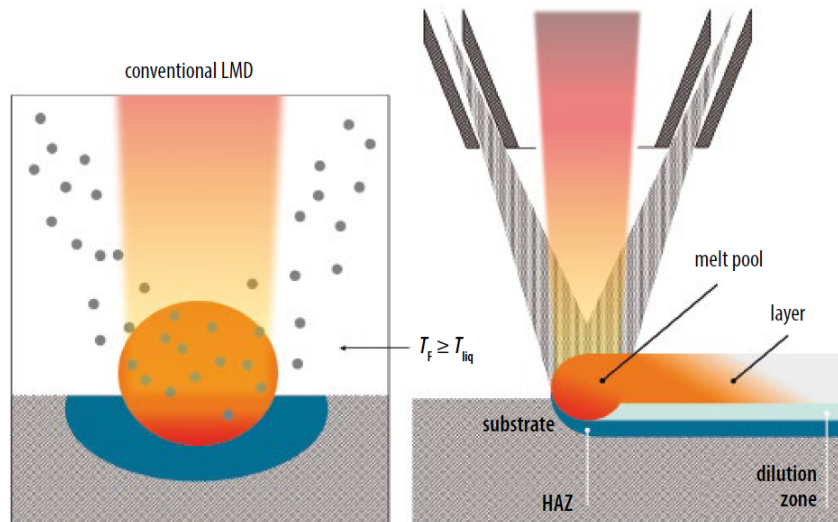
2.1 Process

According to the American Society for Testing and Materials (ASTM) International Committee F42, AM processes can be categorized into seven main types: Powder Bed Fusion (PBF), Direct Energy Deposition (DED), Material Jetting (MJ), Binder Jetting (BJ), Material Extrusion (ME), VAT Photopolymerization, and Sheet Lamination (SL). Among these, Direct Energy Deposition (DED) stands out as one of the most robust methods on the market due to its wide range of applications and significant presence in various industrial sectors. (VAFADAR *et al.*, 2021)

2.1.1 Direct Energy Deposition

There are two most common types of processes using either focalized thermal energy or kinetic energy (cold spray). In cold spray, particles are accelerated at high speed until they obtain the necessary kinetic energy, upon hitting the substrate, they combine to form the required layer. In the thermal energy branch, energy is supplied to the process through a laser beam, electron beam, plasma, or arc. These processes allow for the manufacturing of complex geometries, albeit with low resolution, which can be improved with the use of post-processing. (VAFADAR *et al.*, 2021)

Laser Metal Deposition (LMD) is a type of DED in which a laser is used as an energy source to create a melt pool into which powder particles are injected (see Figure 1). This results in the particles melting and forming a layer upon cooling. The remelting of the base material and powder particles creates a metallurgical bond between the layer and the base material. (SCHOPPHOVEN; GASSER; BACKES, 2017)

Figure 1 – Principle of conventional Laser Material Deposition

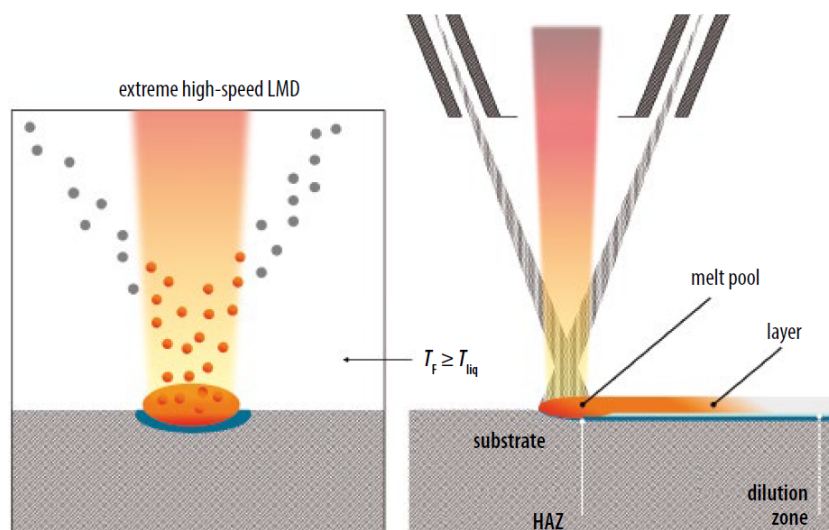
Source: Schopphoven, Gasser e Backes (2017).

2.1.2 Extreme High-Speed Laser Material Deposition

Unlike LMD, the powder particles in Extreme High-Speed Laser Metal Deposition (EHLA) absorb a significant amount of energy from the laser before they reach the base material, so they are already molten when they hit the part (see Figure 2). The laser not only melts the incoming particles but also a portion of the substrate due to the energy input. After hitting the surface, the molten particles create a metallurgical bonded layer. (SCHOPPHOVEN; GASSER; BACKES, 2017)

The particles experience heat from the laser source leading to their rapid melting, additional evaporation accelerates them towards the surface. Consequently, a smaller melting pool is formed, allowing for superior control over substrate penetration. EHLA boasts a remarkable speed, being 100 times faster than the LMD process. Moreover, it facilitates the deposition of surface layers with thickness ranging between 25 and 250 micrometers. (SCHOPPHOVEN; GASSER; BACKES, 2017)

The reduced heat input required for bonding the particles results in a smaller Heated-Affected Zone (HAZ). By adjusting the parameters, the penetration depth can be finely configured, allowing for very low values, such as 5 to 10 μm . Additionally, a catchment efficiency of the particles of over 90% can be achieved. This heightened precision and control make EHLA a technology that offers both speed and meticulous control over the deposition process. (SCHOPPHOVEN; GASSER; BACKES, 2017)

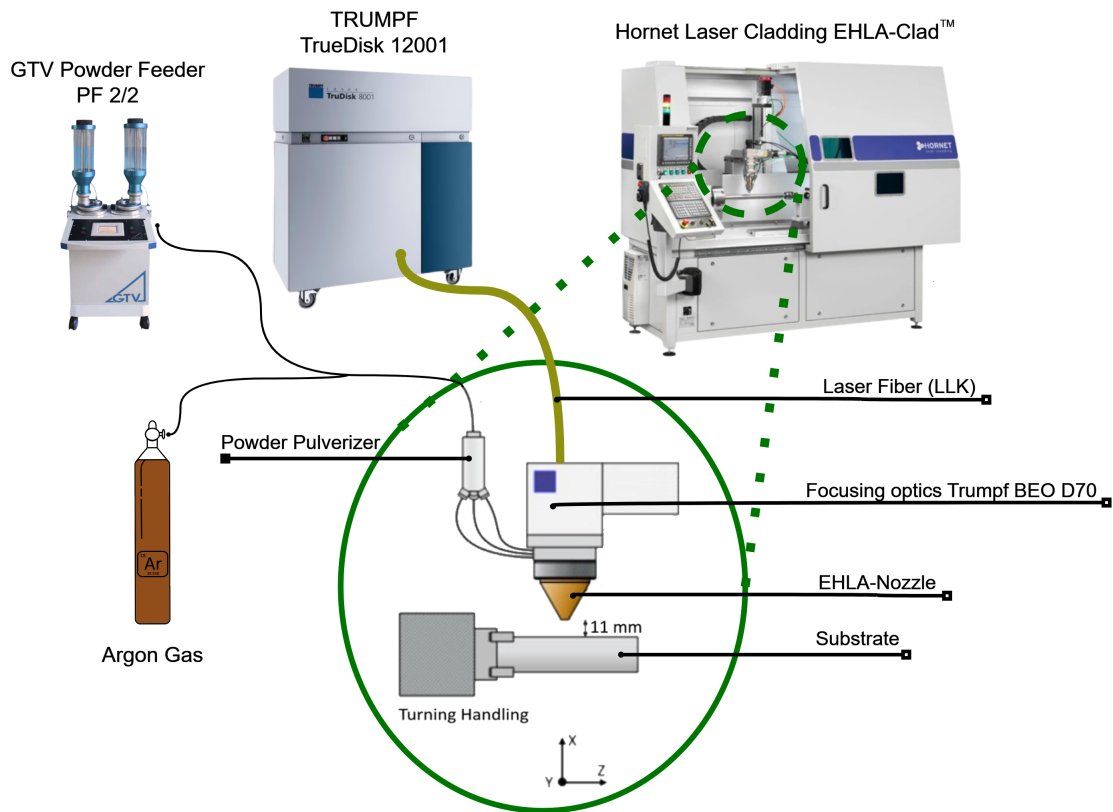
Figure 2 – Process principle of EHLA

Source: Schopphoven, Gasser e Backes (2017).

To achieve EHLA, the setup (Figure 3) shows several components which are essential to the method. These include a powder feeder, responsible for mixing particles and ensuring a consistent feeding rate of powder mass flow. The laser source serves as the heat source, transmitted to the nozzle through a laser fiber. Argon gas functions as shielding gas and carrier gas, transporting particles from the powder feeder to the nozzle.

The CNC system is pivotal for mechanical movements, overseeing tasks such as controlling the laser head and the rotation of the substrate. To manipulate the laser beam, an optic system is used, precisely directing it to the specified spot at the center of the nozzle. Additionally, the right standoff for EHLA is configured appropriately to enable a seamless EHLA process.

Ensuring a successful weld also involves setting up the correct parameters on the machines, a crucial step in achieving optimal performance.

Figure 3 – EHLA setup

Source: Adapted from GTV Verschleißschutz (2024), TRUMPF (2024), HORNET (2024), and Fraunhofer ILT (2024).

2.2 Process analysis tools

Typically, the post-processing method involves equipment such as cutting machines, polishing tools, and microscopes for result analysis. In contrast, the in-line process method requires specialized software and measurement systems, with only specialized programs available for LMD in the market.

2.2.1 After Process

The process of determining the optimal parameters relies on a combination of heuristic methods and iterative experimentation. Once a set of experiments is completed, the initial appearance of the weld are examined to assess whether it appears satisfactory or exhibits issues such as pores or cracks. In more challenging scenarios, the environmental conditions may not have been conducive, resulting in a weld that either fails to melt or does not bond effectively to the substrate, creating only a superficial cover. (FREDERIC; VOORT, 2019)

Visual inspection alone cannot delve deeply into the intricacies of this complex system, as it depends on numerous conditions. Hence, a thorough analysis via metallography is essential. It prompts meticulous preparation to reveal both macrostructural and microstructural aspects of the welding. (FREDERIC; VOORT, 2019)

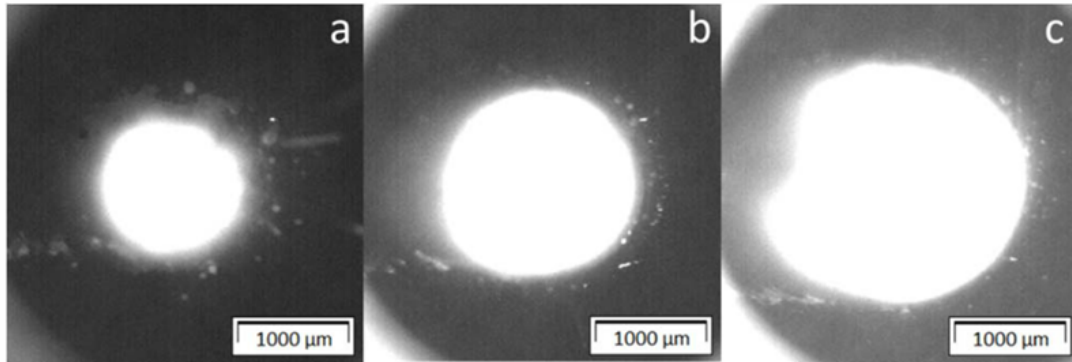
To conduct metallography, a portion of the weld must be cut to provide cross-sections, offering different perspectives for a more detailed visualization. Following the cutting process, the sample undergoes grinding and polishing, often embedded for better management during these procedures. Additionally, selective etching may be employed to enhance the visibility of specific features, such as the HAZ. (FREDERIC; VOORT, 2019)

After embedding and polishing the sample, microscopic analysis reveals diverse quality patterns and characteristics of the weld. This encompasses identifying porosity, detecting cracks, and inconsistencies between layers. (FREDERIC; VOORT, 2019)

2.2.2 During Process

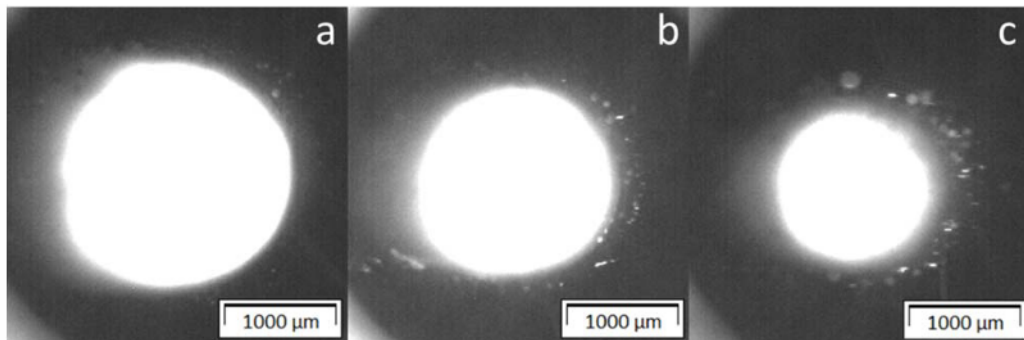
To enhance outcomes in the process, emerging technologies offer various approaches for real-time monitoring and control. Diverse sensors can be employed to provide multiple perspectives on the process, including measurements of flow rate, powder focus, and temperature using a pyrometer. Cameras, whether equipped with thermographic capabilities or not, enable observation of the melting pool and other critical features. These features encompass the tail of the melting pool, temperature variations, melting pool area, brightness, circulation, and constancy. The utilization of such sensors and imaging technologies contributes to a comprehensive understanding and effective control of the manufacturing process. (OCYLOK *et al.*, 2014)

The studied by Ocylok *et al.* (2014) in LMD, show the correlation between melting pool features and laser power and powder flow rate. Figure 4 shows the correlation between melting pool area and brightness as a function of laser power. With increasing laser power, at a constant powder flow rate, a larger melting pool is generated.

Figure 4 – Variation of laser power (a) 700 W; (b) 900 W; (c) 1200 W

Source: Ocylok *et al.* (2014).

On the other hand, increasing the powder flow rate means more delivered material and thus more energy is needed to give enough thermal energy to the particles and the melt pool. By increasing the powder flow rate at constant laser power, the melting pool area and brightness will decrease, as seen in Figure 5.

Figure 5 – Variation of powder mass flow (a) 1.2 g/min; (b) 2.4 g/min; (c) 4.8 g/min

Source: Ocylok *et al.* (2014).

2.2.2.1 Similar Softwares

Several software options are available in the market for image capture, ranging from free solutions like Pylon Viewer to more specialized solutions, such as Xiris and Clamir. However, regardless of whether the software is free or paid, the essential hardware components such as cameras and lenses still need to be acquired.

The Basler Pylon Camera Software Suite, offers a range of tools for managing Basler cameras and capturing images or videos. Features such as Vignetting Correction, Sharpness Indicator, Bandwidth Manager exemplify the array of functionalities that users can readily extract from the suite. (BASLER, 2024)

WeldStudio™ 3 and WeldStudio™ 3 Pro, developed by Xiris in 2024, provide software solutions with image processing, camera and machine vision configuration, and thermal measurement features. The standard software measures weld bead temperatures within a defined Region of Interest (ROI) and displays them on a Human

Machine Interface (HMI). It supports cameras off-axis and coaxial with laser optics systems. (XIRIS, 2024).

Clamir's innovative system offers real-time control of laser power in processes like Laser Metal Deposition (LMD). Using an infrared camera to monitor melt-pool geometry, the results are visually represented in a dedicated software. With this software it is possible to depict how melt-pool behavior directly influences laser power values, highlighting the source adjustments based on the melt pool widget. The software extends control beyond laser power, temperature, monitoring melt pool area, and alarm management. (CLAMIR, 2024)

2.2.2.2 Deficit

Despite the capabilities showcased by the tools cited, the absence of specific testing with the EHLA process signals shows an enduring demand for further exploration and optimization. The critical aspects of simultaneous picture capture and time management are integral in the dynamic landscape of EHLA, where rapid processes necessitate synchronized data acquisition.

3 METHODOLOGY

In this chapter, the methodology and equipment employed for the project is outlined.

3.1 Hardware

To optimize the experimental process, specialized machining equipment played a crucial role. The utilization of high-quality machinery, such as a CNC machine and the entire EHLA setup, ensured the reliability of experiments. Additionally, advanced cameras were employed to acquire precise and high-quality data.

3.1.1 Hornet EHLA Cladding

The Hornet Laser Cladding EHLA-Clad, provided by Hornet Laser Cladding, was the primary machining tool in this project. Tailored to meet stringent requirements for speed, reliability, and efficiency, this machine is a 4-axis system with Fanuc Model B5 Serie 30i CNC control. It excels in handling common geometries like conical shapes, shafts, and disks. Notably, its precision, speed, and control capabilities make it particularly suitable for EHLA, contributing to the credibility of the conducted tests. (HORNET, 2024)

3.1.2 Cameras Basler

Basler AG, a leading company in machine vision technology, specializes in digital cameras (BASLER, 2024). The cameras employed in development are detailed below:

- Cameras Baslers model acA1440-220um: Have a Sony IMX273 CMOS sensor, these cameras offer a maximum resolution of 1,456 x 1,088 pixels, a pixel size of 3.45 x 3.45 micrometers, 10/12 pixel depth, 1.6 megapixels and a frame rate of 227 FPS. The cameras operate with a USB 3.0 connection (USB 3.0 has a data rate of 4.8 Gb/s).

- Camera Baslers model acA720-520um: With the Sony IMX273 CMOS sensor, have the maximum resolution of 728 x 544 pixels, pixel size of 6.90 x 6.90 micrometers, 8/12 pixel depth, 0.4 megapixels and frame rate 525 FPS. Also operates with a USB 3.0 connection.

3.2 Software Used

As this thesis culminates in a software, numerous files and versions of the code will inevitably emerge. In this context, Microsoft Visual Studio stood at the

forefront as the primary programming and debugging tool, providing a platform for both creation and fine-tuning of code (MICROSOFT, 2024). When it came to version control, GitLab, a Git-based system, adeptly navigated the complexities of handling extensive codebases. Its role was indispensable in ensuring meticulous version control and seamlessly managing the evolutionary trajectory of the codebase and efficiency of the work. (GITLAB, 2024)

3.2.1 Languages

In the realm of digital computing, gaining a nuanced understanding of the intricacies of computer memory is essential. This involves not only comprehending how the computer processes commands for basic arithmetic operations but also delving into more intricate and complex tasks. (GRAF, 1999)

C++ boasts prowess with an array of features, including memory management capabilities catering to diverse data types. Additionally, essential resources like pointers, threads, and queues commonly employed in software development are thoroughly explained by Salonen (2018):

- A pointer is a tool that helps programs keep track of where specific information is stored in the computer's memory. It's like a guide or signpost that directs the program to the right place
- A thread allows the program to do different tasks at the same time, making things run more efficiently
- A queue is a way for a program to organize tasks in a line. It follows the principle of "first come, first served," much like waiting in line for a service. The first task added to the queue is the first one to be processed, creating a structured order for tasks to be completed.

Python has standard libraries and a wealth of third-party packages. In the realm of image processing, Python facilitates a systematic approach, streamlining the management of large quantities of images (PEIRCE, 2007). Contributed in the thesis to image processing tasks and managing pattern data.

3.2.2 Libraries

In computer science, a library is a resource collection used in software development, encompassing configuration data, documentation, and source code (SAABITH; VINOTHRAJ; FAREEZ, 2020). It provides a well-defined interface for invoking functions, enabling indirect system calls and facilitating reuse across multiple programs (DESHPANDE, 2013). The following section outlines the libraries incorporated into this thesis:

FOCAS 2 specializes in crafting tailored Windows®-based functions and programs using the programming language C, facilitating seamless communication between PCs and CNC controllers through Ethernet or HSSB (fiber optic) connections. It empowers users to efficiently manage various resources of FANUC CNC systems, including process control and machine inputs. (FANUC, 2024)

Pylon with the programming language C, offers their SDK that allows further development and customization. The SDK, named Pylon, offers tools for managing and integrating cameras into other applications, accompanied by good documentation and sample resources. (BASLER, 2024)

OpenCV, written in the programming language C++ meanwhile boasts bindings in Python, is equipped with documentation and a thriving community. Memory management, image writing, and manipulation are some of its strongest points. (OPENCV, 2024)

PyTorch, a Python library designed for Artificial Intelligence (AI), plays a pivotal position in expediting the image selection process within vast datasets. (PASZKE *et al.*, 2019)

3.3 Software Development

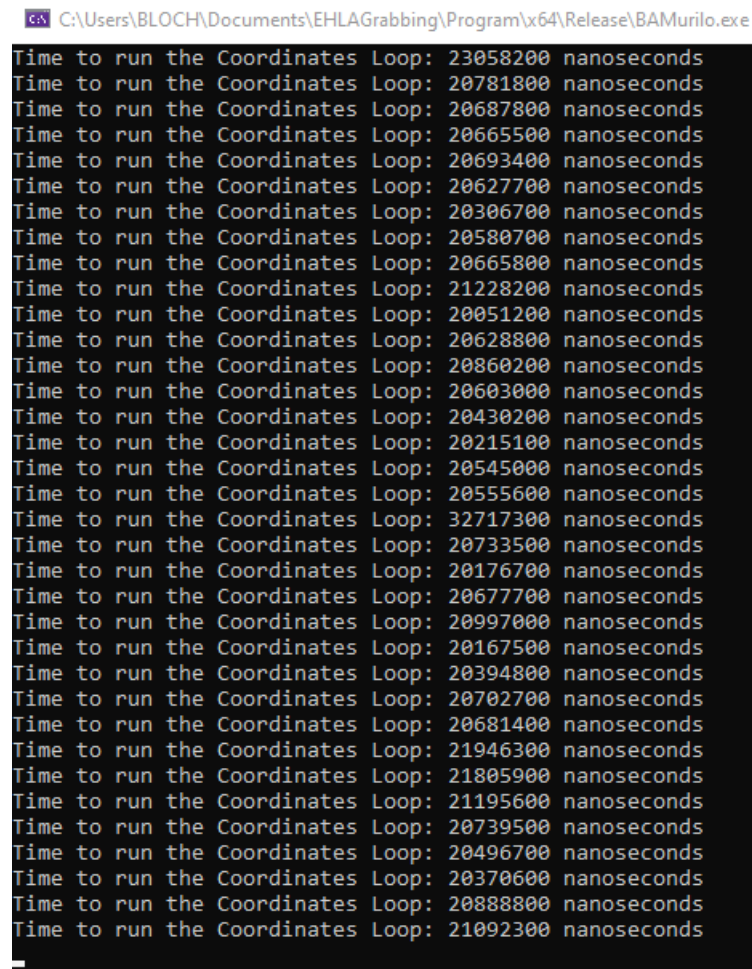
The development focuses on a main program and substantial post-processing analysis.

3.3.1 Main Program

Initial testing with each library involved referencing documentation and exemplary samples, streamlining the development process. The challenges encountered during development prompted a deep analysis of problems, leading to improved solutions. For instance, optimizing image-saving procedures and effectively managing delays became paramount in enhancing the overall code.

A significant consideration was the synchronization of data acquisition from different components, each with its own time delay. The CNC machine and cameras, the Basler acA720-520um and acA1440-220um models, exhibited different frame rates to produce data. This necessitated careful coordination to ensure accurate correlation.

The CNC system requires 21 milliseconds to capture and display a single sample of coordinate status. This performance is visually represented in Figure 6, where a command prompt printout illustrates the output time in nanoseconds, hovering around the mark of 21,000,000 ns. Also, the HMI is on the right with the current coordinate of the CNC.

Figure 6 – Print Screen: Test delay CNC


```

C:\Users\BLOCH\Documents\EHLAGrabbing\Program\x64\Release\BAMurilo.exe
Time to run the Coordinates Loop: 23058200 nanoseconds
Time to run the Coordinates Loop: 20781800 nanoseconds
Time to run the Coordinates Loop: 20687800 nanoseconds
Time to run the Coordinates Loop: 20665500 nanoseconds
Time to run the Coordinates Loop: 20693400 nanoseconds
Time to run the Coordinates Loop: 20627700 nanoseconds
Time to run the Coordinates Loop: 20306700 nanoseconds
Time to run the Coordinates Loop: 20580700 nanoseconds
Time to run the Coordinates Loop: 20665800 nanoseconds
Time to run the Coordinates Loop: 21228200 nanoseconds
Time to run the Coordinates Loop: 20051200 nanoseconds
Time to run the Coordinates Loop: 20628800 nanoseconds
Time to run the Coordinates Loop: 20860200 nanoseconds
Time to run the Coordinates Loop: 20603000 nanoseconds
Time to run the Coordinates Loop: 20430200 nanoseconds
Time to run the Coordinates Loop: 20215100 nanoseconds
Time to run the Coordinates Loop: 20545000 nanoseconds
Time to run the Coordinates Loop: 20555600 nanoseconds
Time to run the Coordinates Loop: 32717300 nanoseconds
Time to run the Coordinates Loop: 20733500 nanoseconds
Time to run the Coordinates Loop: 20176700 nanoseconds
Time to run the Coordinates Loop: 20677700 nanoseconds
Time to run the Coordinates Loop: 20997000 nanoseconds
Time to run the Coordinates Loop: 20167500 nanoseconds
Time to run the Coordinates Loop: 20394800 nanoseconds
Time to run the Coordinates Loop: 20702700 nanoseconds
Time to run the Coordinates Loop: 20681400 nanoseconds
Time to run the Coordinates Loop: 21946300 nanoseconds
Time to run the Coordinates Loop: 21805900 nanoseconds
Time to run the Coordinates Loop: 21195600 nanoseconds
Time to run the Coordinates Loop: 20739500 nanoseconds
Time to run the Coordinates Loop: 20496700 nanoseconds
Time to run the Coordinates Loop: 20370600 nanoseconds
Time to run the Coordinates Loop: 20888800 nanoseconds
Time to run the Coordinates Loop: 21092300 nanoseconds

```

Source: Own (2024) and Fraunhofer ILT (2024).

While the cameras, acA720-520um operated at 520 FPS, corresponding to a frequency of approximately 1.9 milliseconds per frame. On the other hand, the acA1440-220um, with a lower frame rate, 220 FPS, offered enhanced image resolution, with a frequency of 4.5 milliseconds. A mechanism of time attribution was adjusted to accommodate these variations, a timestamp value from a shared clock ensured synchronization across all instances in the code.

Subsequent developments were meticulously crafted with a focus on these time correlation, emphasizing the necessity for precise configuration of cameras and CNC systems. This alignment is vital for projects that involve shared time and data acquisition from peripherals.

To address user-provided input variations, a HMI emerges as a swift and user-friendly solution. The control panel streamlines software management, guaranteeing a seamless user experience and efficient utilization of diverse hardware components.

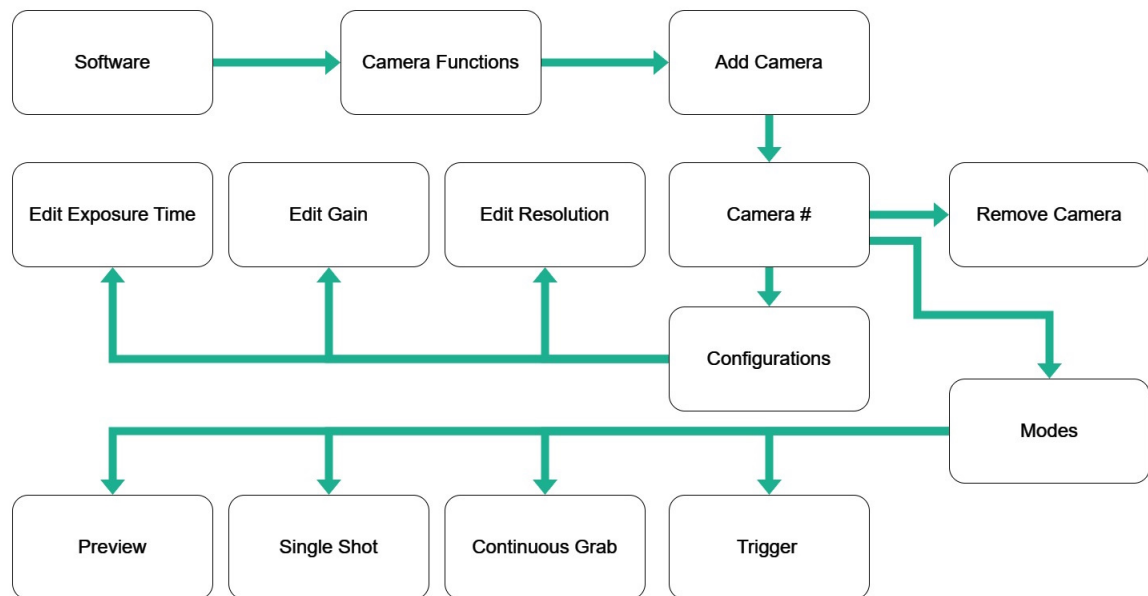
3.3.1.1 HMI Tools

Functions meticulously crafted within the software empower users to seamlessly navigate through the software interface, providing access to a spectrum of functionalities.

Camera

Figure 7 illustrates the camera instance within the system. Upon program initiation, the addition feature is activated, streamlining the integration of up to four devices into the experimental setup. Additionally, the system enables the hassle-free removal of cameras when needed, ensuring their accessibility to other programs on the computer.

Figure 7 – Flowchart camera management



Source: Own (2024) and Fraunhofer ILT (2024).

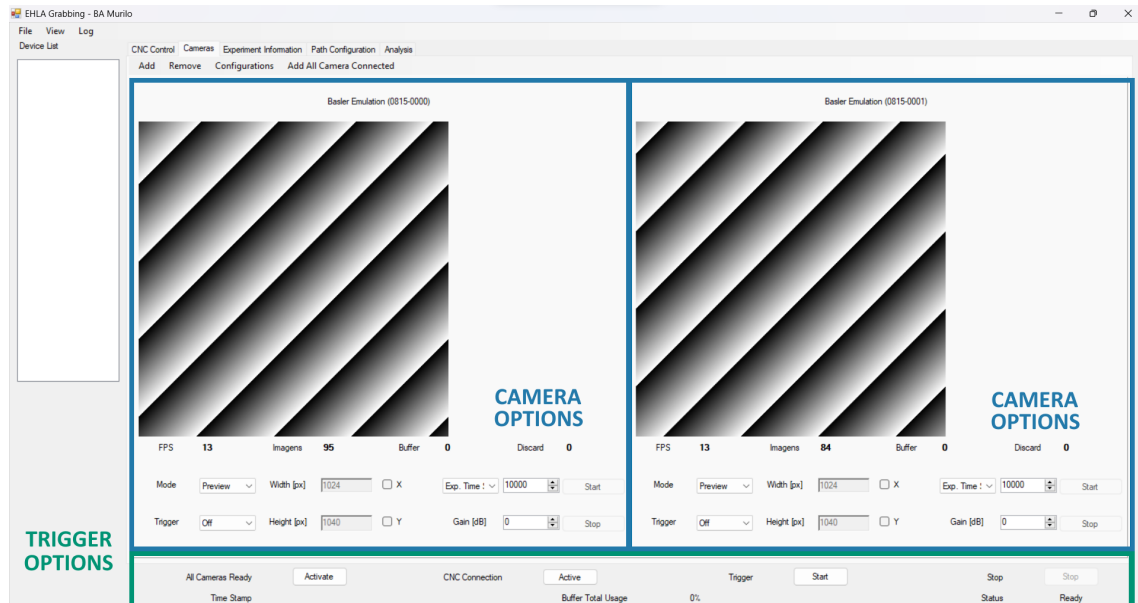
Users can fine-tune the exposure time for each camera instance, gaining control over how long the camera's sensor is exposed to light during image capture. Signal amplification, also known as gain, serves to enhance the brightness of the captured images (TOMASI *et al.*, 2021). These parameters are editable in "Camera Options" in the Human-Machine Interface (HMI), see Figure 8.

It's possible to have multiple cameras and also stand alone capture, isolated grabbing can create continuous frame acquisition until the user stops the process. While a grabbing process is ongoing, images are not displayed on the screen, focusing on updating functionalities for performance improvement in saving.

To display images from the camera, with approximately 1 s of delay, the pre-view mode helps to right configuration of the instrument, like sharpness and illumination.

Also, can take single images, useful to establish relations between areas in pixels, also, rotational position of the images can be configured.

Figure 8 – Camera device in the software



Source: Own (2024) and Fraunhofer ILT (2024).

CNC

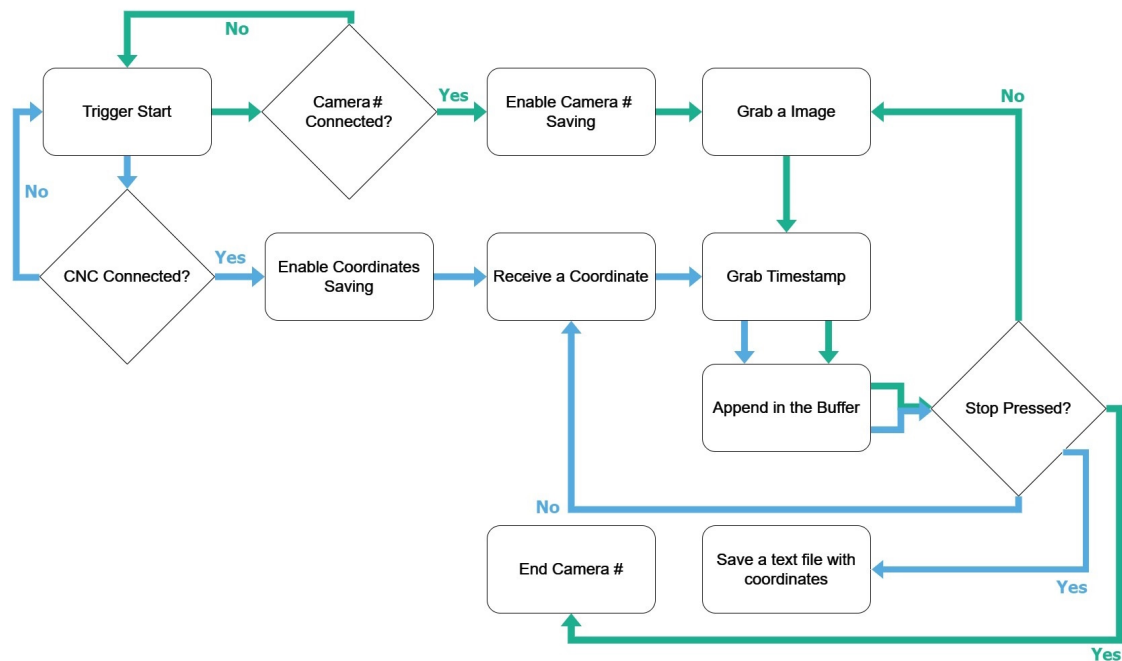
The CNC machine is a key component of the experimental setup, all the physical interaction with the workpiece occurs inside of it. The Fanuc controller has a screen to manipulate and set commands in the machine, and via an Ethernet cable and an Internet Protocol (IP), can provide functionalities to deeply interact with the output data.

Once connected with the controller, the program starts to display relative, machine and absolute coordinates, and also, information about the running program with the remaining distance that the axis needs to follow.

3.3.1.2 Triggering

When all devices are configured, the option trigger "Start", See Fig 9, enables the cameras with the option Trigger on, to simultaneously trigger the capture devices to grab. Simultaneously, once established the connection with the controller, it will start to save all the coordinates received in each test round.

Figure 9 – Data management



Source: Own (2024) and Fraunhofer ILT (2024).

At the commencement of each grabbing process, a timer is started in the main code, being references to the data arriving. The CNC controller sends a coordinate sample, and a value of timestamp is attributed to it. This timestamp value means one acquisition of the value of the timer at the moment of arrival of the data.

In the realm of cameras, the process encompasses distinct structures. With the reception of each image, both a timestamp and the image itself are added to a buffer, facilitating the function's ability to retrieve subsequent images. The buffer denotes the construction of a memory line, aligning the chosen structure, specifically the *struct*. By (SALONEN, 2018), *struct* data is a correlation of various types of data into a single block in the memory.

To manipulate image objects within the code, a shared smart pointer provided by C++ was utilized. Similar to traditional pointers, which create a singular pointer to allocate a specific memory address, this smart pointer proves valuable in managing multiple accesses due to its automatic memory management (SALONEN, 2018). This data, memory type in binary, consists of 0s and 1s. Its ease of understanding and processing commands for the program language, and also, makes it easily transformable into an image. (MOHIDEEN; PETER; WEICKERT, 2021)

In the thesis computer's test environment, the OpenCV library demonstrated efficiency in saving BMP format images, clocking in at a median time of 200 nanoseconds while other formats milliseconds. Furthermore, the BMP was selected as the preferred format for saving images captured from the camera.

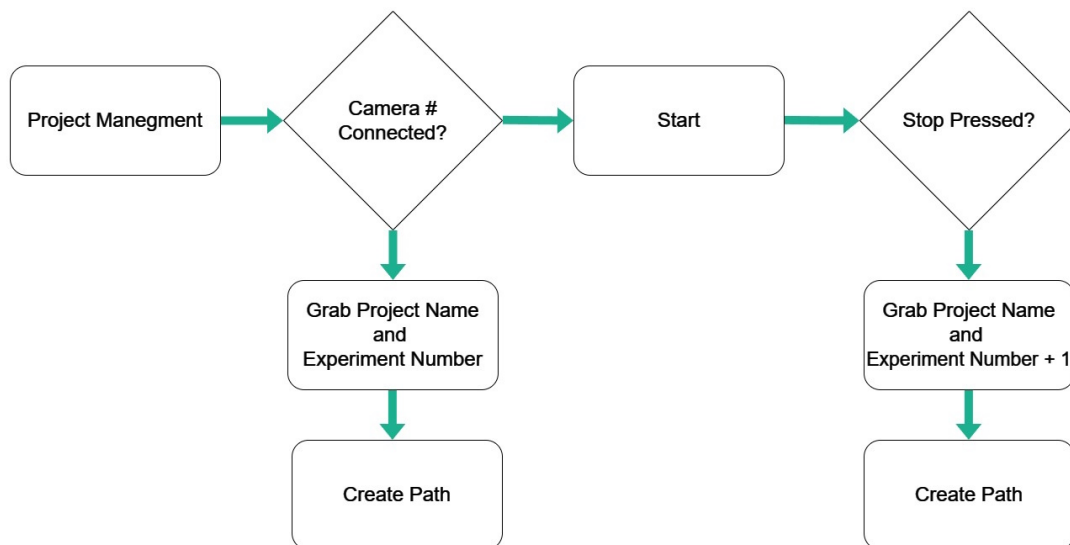
If the computer's writing speed is sufficient, the program can instantly save the image as soon as it is introduced into the buffer. Conversely, if the writing speed is hampered by a large amount of data, the buffer will begin to fill up. Once it reaches full capacity, it will discard images until free memory becomes available, ensuring that other computer resources are not compromised.

Upon pressing the "Stop" button, See Figure 8, conclude the grabbing process, the system consolidates all coordinate data, saving the content into a text file with the text format. It then waits until the buffer is empty, making it available for a new grabbing process.

3.3.1.3 Outputs

When an experiment is initiated, a new folder is generated within the main directory. The user has the flexibility to select the location and assign a name. Subsequently grabbing experiments results in sequential paths such as experiment 1, experiment 2, experiment 3, etc. This concept is more comprehensible in Figure 10.

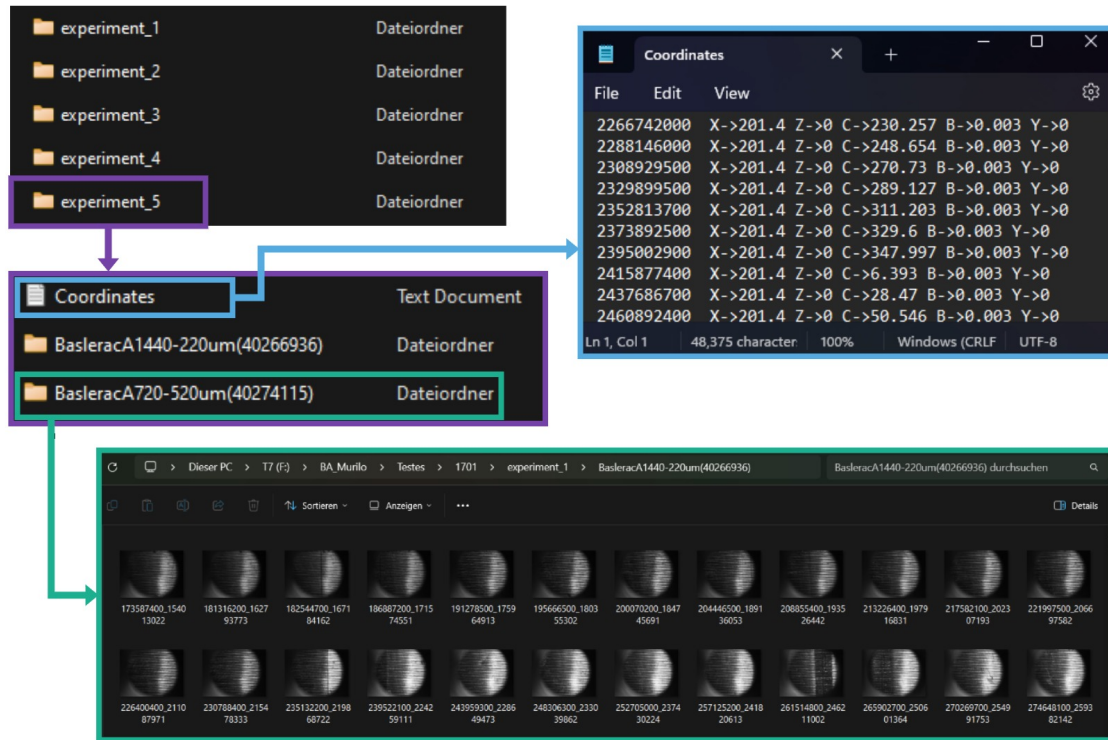
Figure 10 – Path management



Source: Own (2024) and Fraunhofer ILT (2024).

Within each experiment path, individual paths will be created for each connected camera with his content, along with the corresponding text file for the CNC, see Figure 11.

Figure 11 – Data format



Source: Own (2024) and Fraunhofer ILT (2024).

All images captured during the process will be stored in their respective camera folders with two values: "000000000_000000000". Initially, each image will receive a timestamp by the system program, followed by an underscore, and then by the timestamp from the camera's internal clock. The values of the relative coordinates will be archived in a single file, with each line consisting of six values: "000000000 X->0.000 Z->0.000 C->0.000 B->0.000 Y->0.000". The first label represents the timestamp from the computer, followed by the coordinates for the X, Z, C, B, and Y axes respectively, each with their corresponding values at that particular time interval.

3.3.2 Post-processing with Python

Python facilitates image manipulation and editing, alongside the main C++ program, enabling effective correlation and analysis of data, conversion and modifications to ensure meaningful analysis of the process.

Interpolation of coordinates

In the EHLA process, the substrate is rotated with a constant velocity speed. Knowing that the velocity in the process is constant, it brings the approach that with a low quantity of points, it's possible to generate multiple quantities of data doing a linear interpolation between consecutive points.

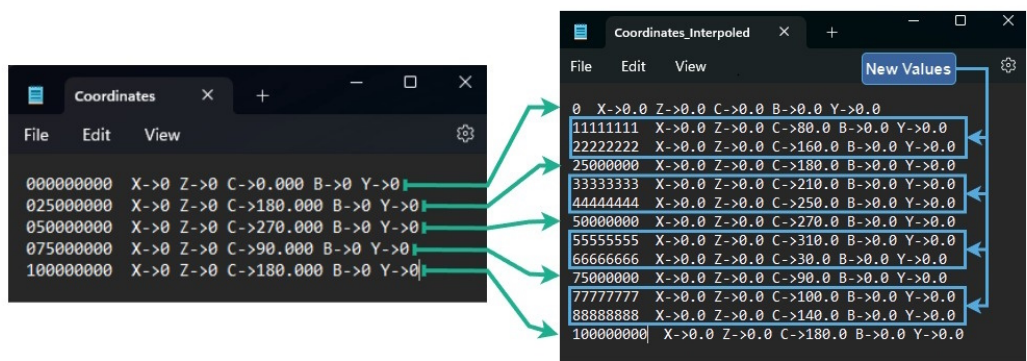
By determining the minimum and maximum timestamp values, a function

creates points between consecutive values given to the function. The interpolated samples are then saved in a new text file called "Coordinates_Interpolated". (See Figure 12)

Envision a scenario wherein the original text file encapsulates coordinates spanning the temporal interval of 0 to 1 second, featuring five values. Being requested for additional eight values, the program's interpolator adeptly generates new coordinates, seamlessly filling gaps between each consecutive pair. These newly computed coordinates are strategically positioned, facilitating a smoother transition amidst the existing data points.

A particularity within the framework created, is that the program deftly handles the circular nature of axis coordinates, confining them within the boundary of 0° to 360° rotational coordinates. As a given value nears 360° , the subsequent value wraps around, commencing a new at 0° , ensuring an uninterrupted and cohesive representation of the circular data.

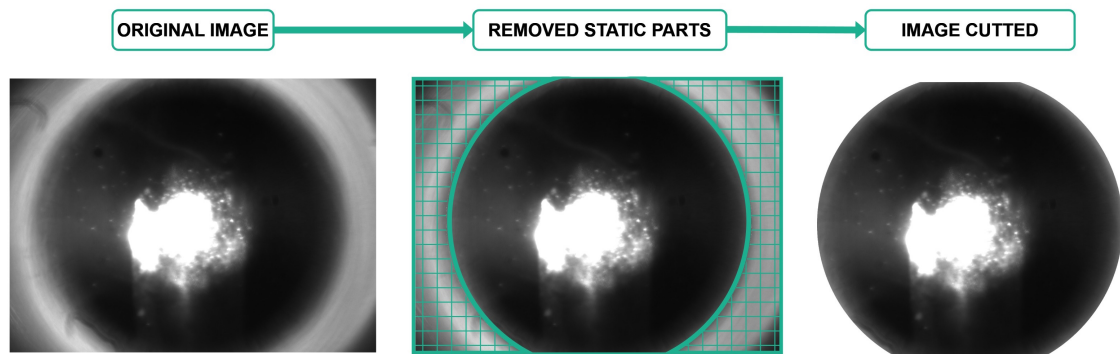
Figure 12 – Coordinates Interpolation



Source: Own (2024) and Fraunhofer (2024)).

Image Editing

A method employed a targeted approach, focusing on miscellaneous features of the image. Cutting, resolution editing, application of mask filters are tools for making the desired attributes visible. For example, with some variable resolution values during each grabbing process, to streamline AI analysis, the resolution of all images of the test in focus was reduced to 200 x 150 pixels. Another consideration was the presence of static portions, such as the camera attachment within laser optics displaying part of the nozzle in every image. While this could be a subject of study, it was not utilized in this work. The removal process often manifested as a circular cut for image evaluation, as illustrated in Figure 13.

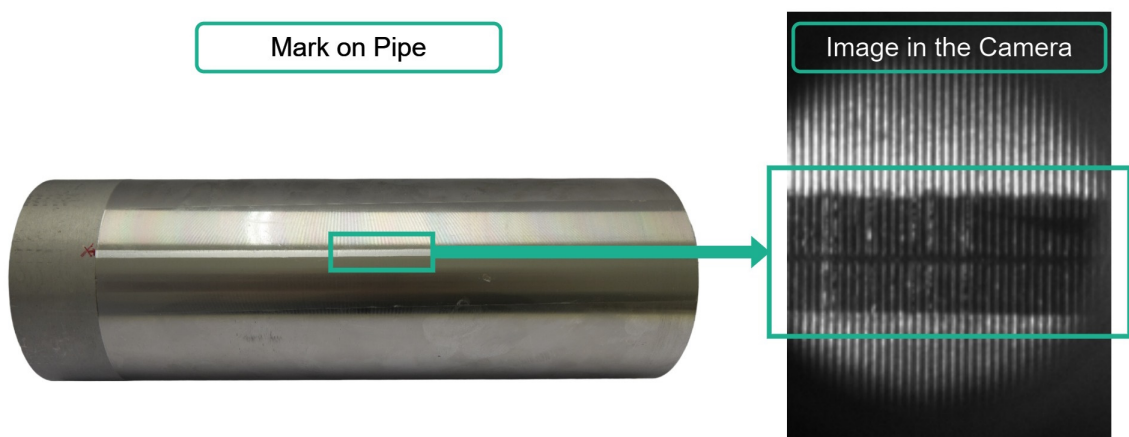
Figure 13 – Image cutting

Source: Own (2024) and Fraunhofer ILT (2024).

Image AI Selecting

Utilizing PyTorch, one can train an AI model for image classification (PASZKE *et al.*, 2019). By empowering the intelligence to discern specific images, users can input complete image paths and instruct the model to execute various actions based on the assessment of each image.

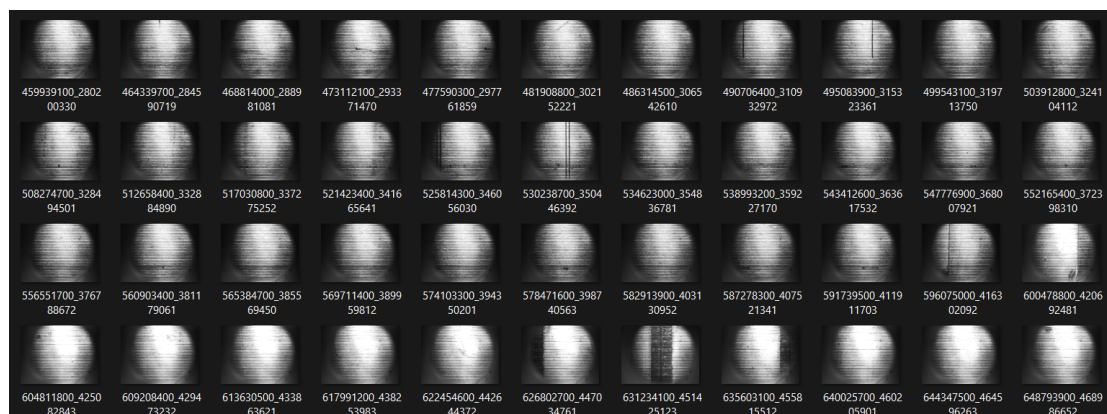
With farsightedness in mind, a dedicated code was developed to read, assess, and store selected images in a designated folder, anticipating the validation of time attribution reliability. To enhance visibility, a distinctive physical marker, an aluminum sheet, was strategically placed within the substrate (see Figure 14) with the aim of capturing this trace in the camera images.

Figure 14 – Tube mark and his image search results

Source: Own (2024) and Fraunhofer ILT (2024).

A singular axial point-of-view camera captures multiple images to construct a comprehensive map of the substrate surface. Illustrated in Figure 15, these images reveal various superficial characteristics of the component.

Figure 15 – Superficial images of the substrate in the camera path

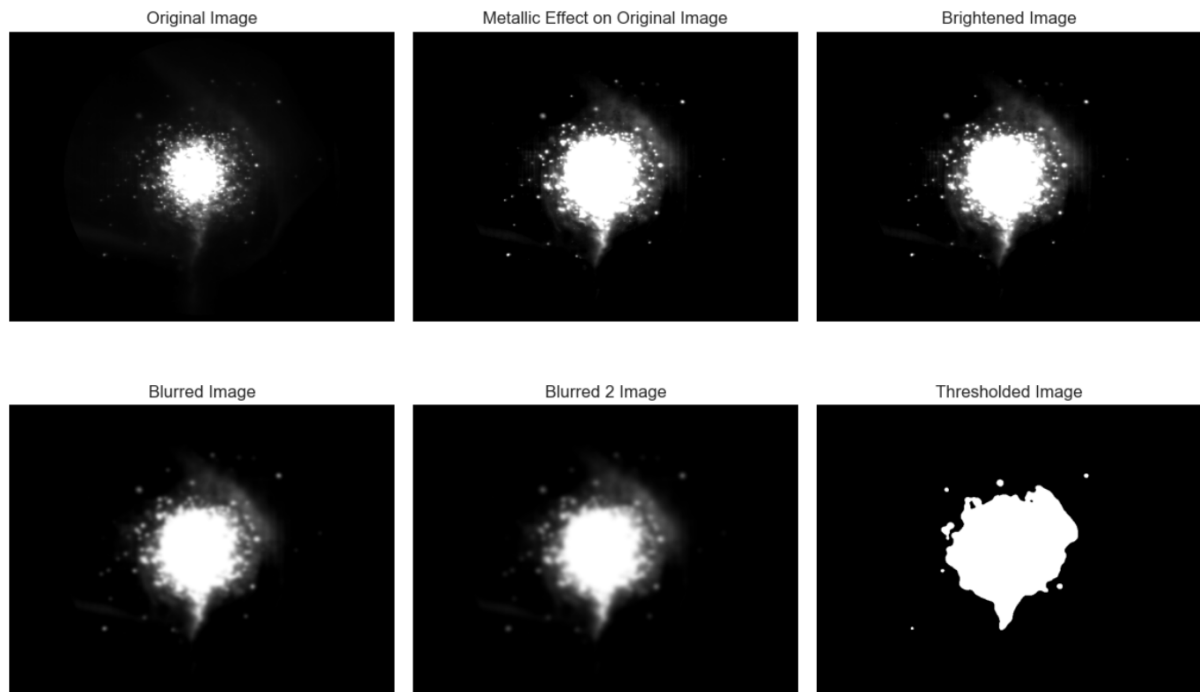


Source: Own (2024) and Fraunhofer ILT (2024).

The selected images are then transferred to a distinct folder while retaining their original labels. This preserves the ability to compare them with the CNC controller through the timestamp, ultimately streamlining the data processing workflow and saving valuable time.

Image Analyze

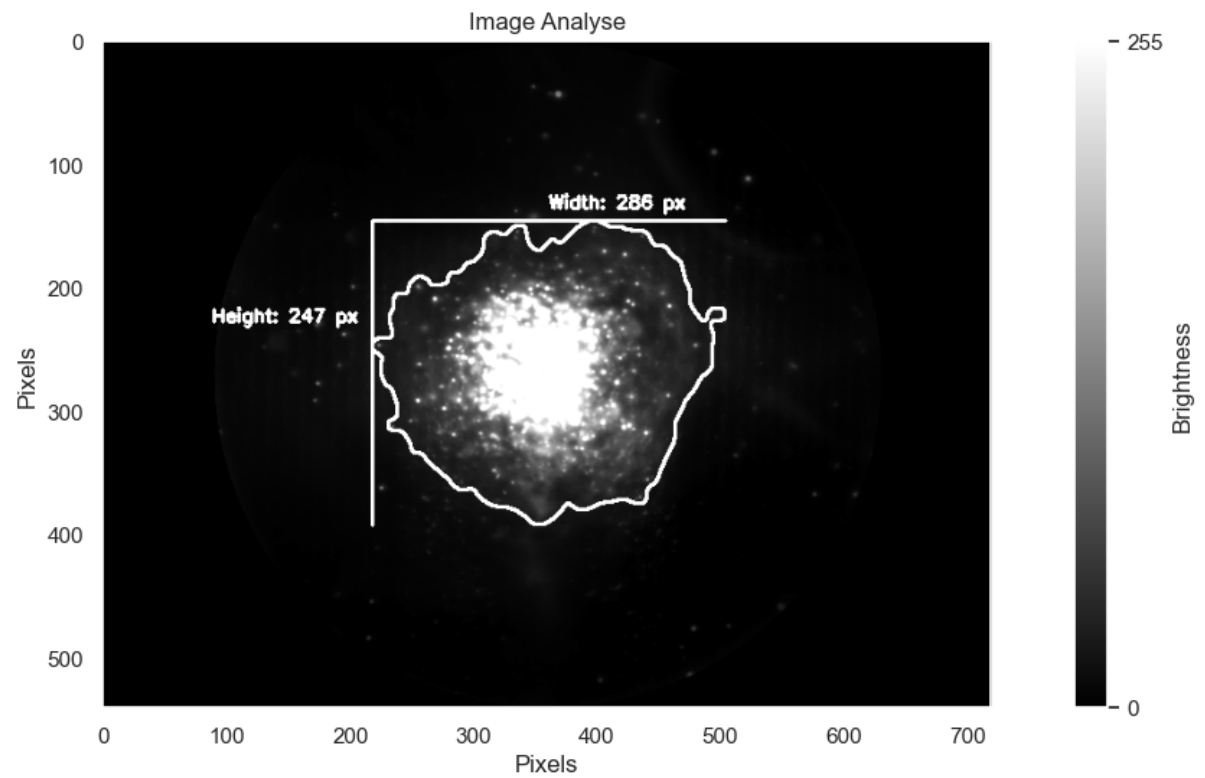
When it comes to image analysis, accurately translating visual features into known dimensions through precise measurements. A fundamental aspect of this process involves configuring filters appropriately, enabling the identification of contours and the measurement of various geometrical properties of the object under examination. As illustrated in Figure 16, the process unfolds sequentially: the initial step imparts a metallic effect to the image, followed by incremental adjustments in brightness and blur to derive a binary threshold. This threshold operation results in the creation of a new image, where each pixel is transformed to either black or white (0 or 255).

Figure 16 – Applied filters on images

Source: Own (2024) and Fraunhofer ILT (2024).

Refining the application of filters and masks yields a nuanced comprehension of the underlying process, revealing specific characteristics contingent upon the applied configuration. Within the scope of this thesis, attention is focused on three distinct aspects: the size and circularity of the melt pool area, alongside the intensity of brightness across the entire image. It is crucial to acknowledge that in the evolution of EHLA, the placement of the laser source at the powder focus may yield a blurred or less precise representation of reality. Consequently, this analysis strives to attain the most accurate depiction of real features possible.

In Figure 17, the image captured by the acA720-520um camera displays the melt pool, delineated by contours, with a measurement of its dimensions.

Figure 17 – Image of melt pool analysis

Source: Own (2024) and Fraunhofer ILT (2024).

4 RESULTS

This chapter provides an overview of the results obtained in the project, presenting a summary of the tests conducted and their outcomes.

4.1 Validation

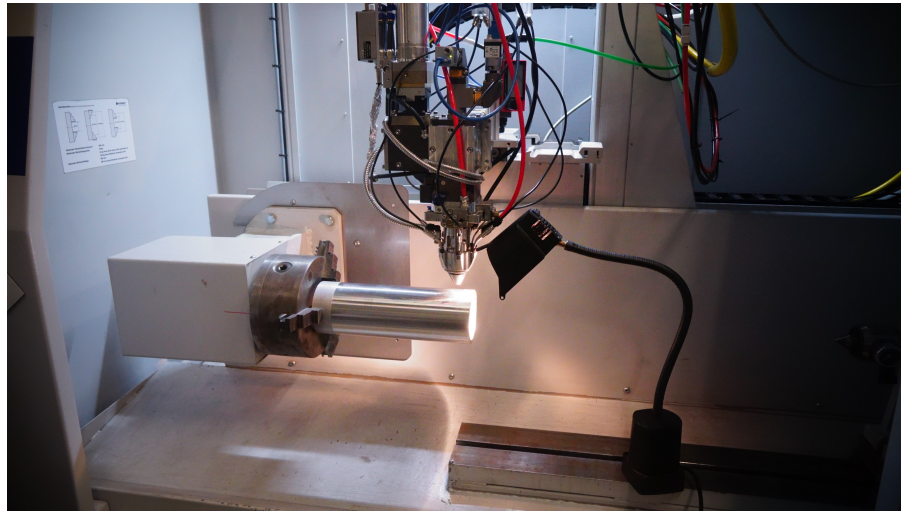
The validation process comprises two distinct steps. The first step involves validating the data within the software, ensuring that the time mechanism aligns with expectations and exhibits reliability. The second step employs a genuine EHLA process, extracting metrics from the initial test to detect potential defects in the structure.

4.1.1 Program Analysis

In the realm of scientific advancement, the rigorous evaluation of a system demands a dependable reference, derived from reliable source metrics. The initial phase involves scrutinizing time attribution, employing cameras set to an identical frame rate of 220 FPS. This approach facilitates a clearer understanding of whether the timestamp is accurately received.

Ensuring synchronization entails aligning both cameras at the same frequency and capturing the substrate surface from the same position area. This alignment ensures that the timestamp captured in one image corresponds precisely to the near image in the other camera.

To execute this test, it is needed to fine-tune the cameras within the optical system of the laser, observing the results on the display to confirm synchronized rotational positions and adequate brightness. Importantly, the process itself does not activate the laser, maintaining safety by requiring closed doors in the CNC machine to operate. To address the resultant low light conditions, a lamp has been strategically installed, enhancing visibility, as depicted in Figure 18.

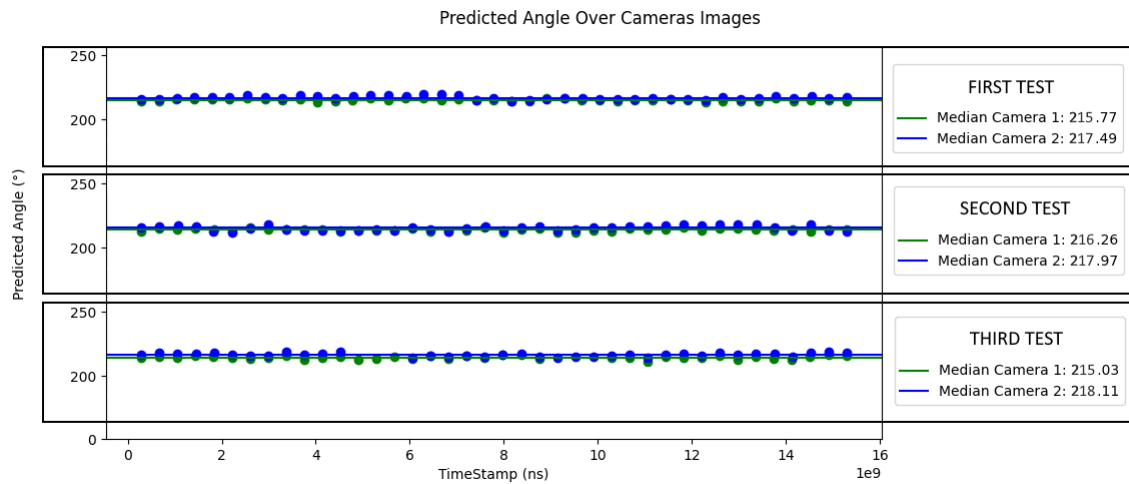
Figure 18 – Illuminated environment

Source: Fraunhofer ILT (2024).

Following this procedure, the machine was initiated, and cameras captured images while the substrate surface rotated at a velocity of 50 m/min relative to the laser head. Three attempts were executed within a 15-second period.

Subsequently, utilizing the output data, an AI data classification model was trained to scan and curate images featuring marks along the camera paths. The model selected multiple images, each with corresponding timestamps denoting the moment of capture of each camera.

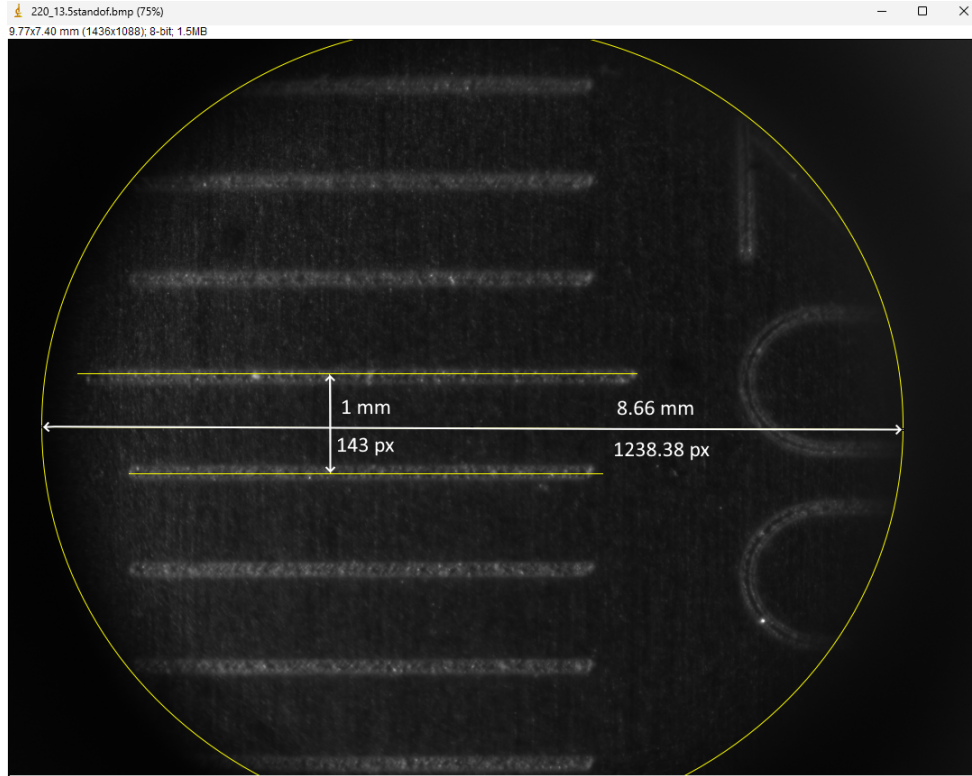
To further analyze these images, their timestamps were correlated with interpolated coordinates. The timestamp of the marked image could then be translated into a coordinate value. A search in the coordinate text file was conducted to identify the nearest timestamp to the image in question. This comprehensive dataset was scrutinized, and all pertinent points were gathered and visually represented in Figure 19.

Figure 19 – Multiple tests at 50 m/min

Source: Own (2024) and Fraunhofer ILT (2024).

The Figure 19 illustrates the mean values of computer timestamps recorded by Camera 1 at 215.77°, 216.26° and 215.03°, and by Camera 2 at 217.49°, 217.97° and 218.11° during the tests. Consistency is observed in the computer timestamps, with the median readings around 215.69° for Camera 1 and 217.87° for Camera 2, resulting in a difference in modulus of approximately 2.18° between them.

To assess the magnitude of this value, an image was captured with a nozzle stand-off of 13.5 mm using the acA1440-220um camera, which offers a resolution of 1,436 x 1,088 pixels. In Figure 20, shows that get an estimated ratio of 143 pixels per millimeter in the image. Additionally, a circle was delineated to demarcate the useful viewing area facilitated by the nozzle via the optic system, resulting in an 8.66 millimeter segment of the tube's circumference.

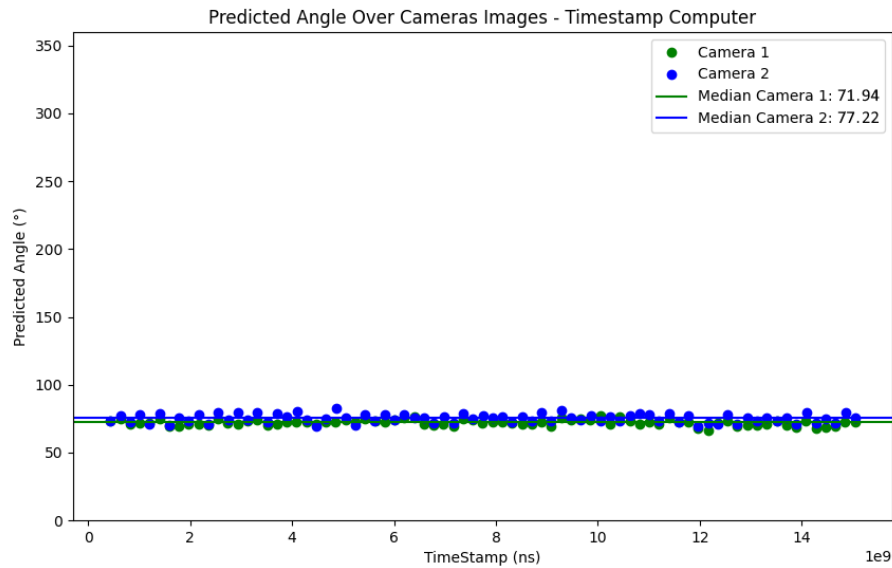
Figure 20 – Image measurement

Source: Fraunhofer ILT (2024).

Employing the formula for the perimeter of a cylinder in Equation 1 while considering a tube diameter of 99.4 mm, it yields a perimeter of 312.27 mm. With approximately 1.15° , for each millimeter in the image, it is associated with an angular amplitude of 9.96° within 8.66 mm in Figure 20. Consequently, an acceptable variance of 2.18° is enough, because the markings on the images are not perfectly centered.

$$P = 2 * \pi * r \quad (1)$$

By comparing the outcomes of two similar FPS settings, it becomes feasible to transition one camera to the acA720-520um and evaluate the results. To realize this, one test was conducted at rotational speeds of 100m/min. In Figure 21 Camera 1 is depicted with 520 FPS, while Camera 2 represents the 220 FPS.

Figure 21 – Test 100 m/min with the cameras 520 FPS and 220 FPS

Source: Own (2024) and Fraunhofer ILT (2024).

These findings reveal further fluctuations in the projected angles, showing a disparity of 5.28° in magnitude. Yet, this deviation falls within an acceptable spectrum. It's now understood that both cameras can function simultaneously, yielding coordinate data for corresponding images, even at varying frame rates, where reduced deviations are observed.

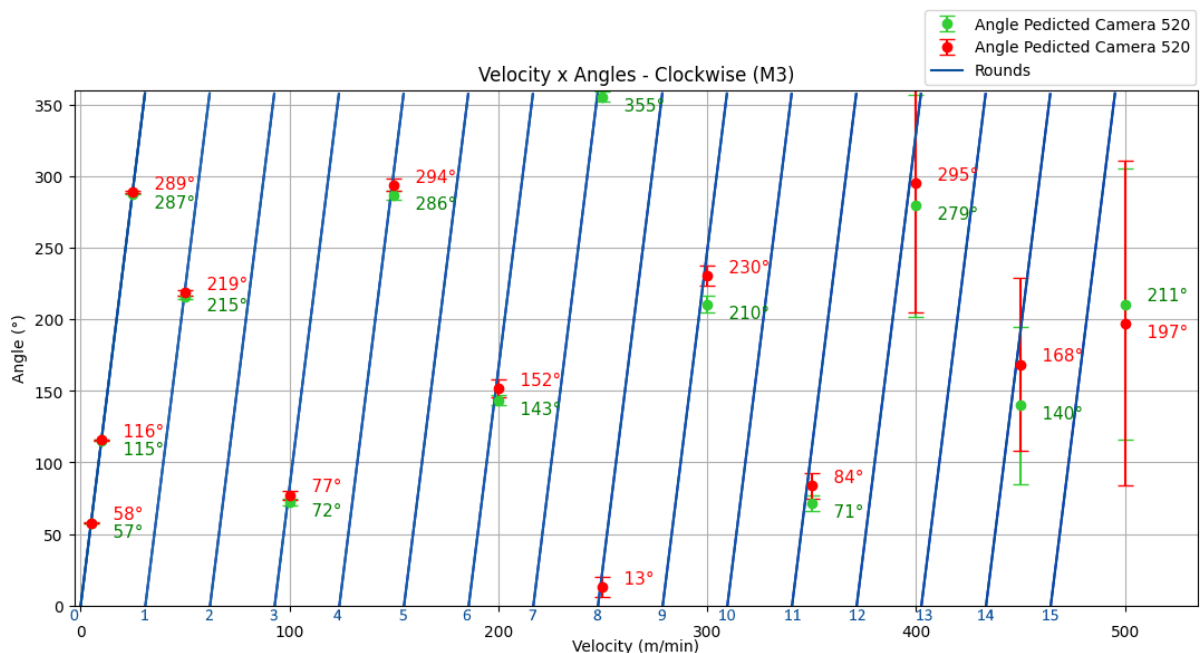
Despite acknowledging the alignment of the results, where the expected value should be 0° , the system produces varying values. The focus now turns to resolving this issue of deviation from 0° with new tests spanning velocities from 5 m/min to 500 m/min.

Tests were carried out in the clockwise direction at velocities of 5, 10, 25, 50, 100, and 150 m/s, with increments of 50 up to 500 m/s. Conversely, for the counterclockwise direction, tests were conducted at velocities of 5, 25, 50, and 100 m/s, with increments of 100 up to 500 m/s. Subsequent analysis will adopt a macro perspective, aiming to discern any temporal associations, particularly the correlation between increasing or decreasing velocity and the corresponding rise or fall in coordinate values.

It's essential to highlight that increasing the substrate rotation velocity leads to the spindle completing more rotations within the same time frame, potentially affected by a constant delay. In the realm of G-Code, the language translating human instructions into meaningful machine commands, activating the M3 mode for clockwise substrate spinning reveals a pattern. As the velocity increases, there is a consistent upward trend in the coordinates. Subsequently, a similar test was conducted using the command M4, designed for counterclockwise rotation. Remarkably, the findings unveiled an downward trajectory in coordinates corresponding to an escalation in velocity. This pattern is

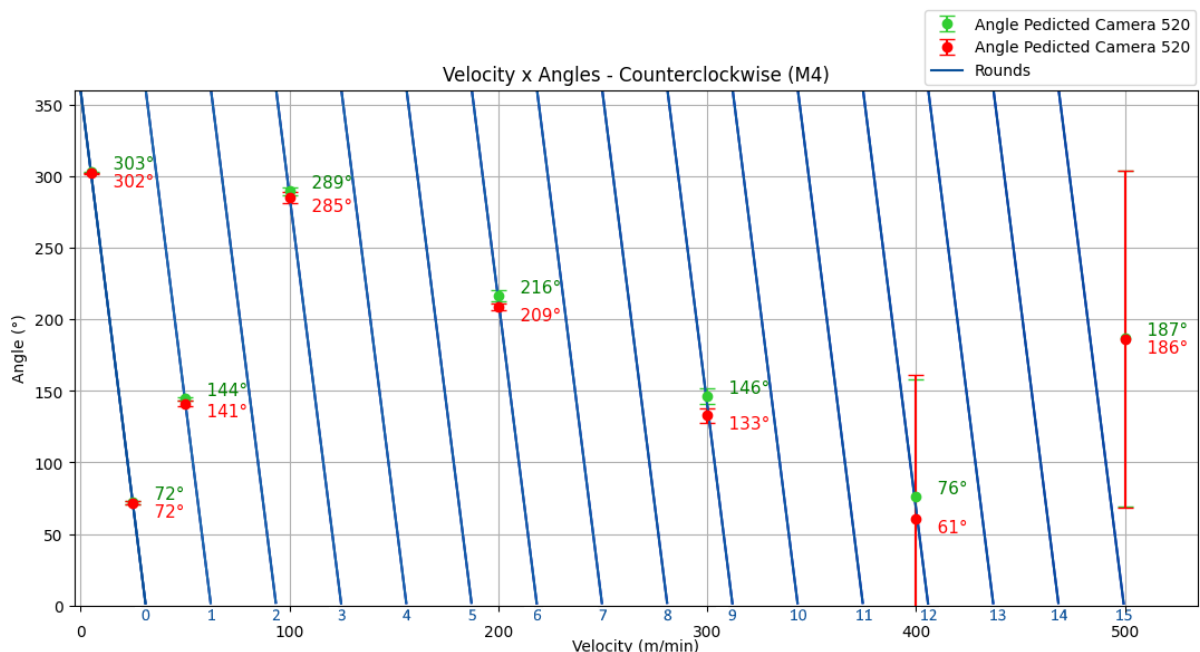
visually in Figure 22 and 23.

Figure 22 – Tests clockwise - Rotational velocities



Source: Own (2024) and Fraunhofer (2024).

Figure 23 – Tests counterclockwise - Rotational velocities



Source: Own (2024) and Fraunhofer (2024).

The rotational coordinates demonstrate a cyclical pattern, resetting to 0° upon reaching 360° in the clockwise direction, mirroring a sawtooth waveform. This

pattern reverses in the counterclockwise direction. Initially, the behavior of the delay can be described using a linear equation derived from velocities of 5 m/min and 10 m/min, along with their respective angles. Equation 2 represents this relationship for clockwise motion, while Equation 3 portrays it for counterclockwise. In the equations Y denotes the coordinate value in degrees, and X represents the process surface velocity in meters per second.

$$Y = 11.628 \cdot X \quad (2)$$

$$Y = -11.531 \cdot X + 360 \quad (3)$$

However, with each passage through the 0° mark, the equation produces values that surpass the predefined range. Every 360° encompassed within this value signifies an additional rotation before reaching the designated coordinate, denoted by the blue lines in the Figures 22 and 23, labeled "Rounds" with corresponding numbers on the x-axis. This model adapts to successive data points when applied to varying velocities. Moreover, scrutinizing the time intervals between consecutive images aligns with the suggested perimeter and speed for each interval.

The gradient for M3 and M4 stand at 11.628 and -11.531 respectively, derived from Equation 2 and Equation 3. The similarity between these coefficients implies a consistent delay for M3 and M4, affirming the program's reliability. The y-intercept coefficient approaching 0° in clockwise and 360° in counterclockwise directions suggests that as the velocity approaches 0 m/s, the delay likewise approaches 0 seconds.

Despite variations in the delay corresponding to different velocities, a linear trend persists. By acknowledging and quantifying these values for each velocity, the extent of coordinate deviation from the 0° position can be precisely determined. Given its linear nature, there's no need to repeatedly replicate the velocity in the tests. Utilizing the equation of the line, the exact coordinate at any given moment can be determined with an offset in the coordinate value.

Furthermore, the standard deviation in Figures 22 and 23 reveals a velocity limit, as the variance significantly exceeds 9.96° . Beyond approximately 350 m/s, the coordinates no longer align with the images. However, even with this limitation, a considerable number of tests in the EHLA process utilize velocities below 350 m/s. Beyond this threshold, the correlations lose coherence, and solely the images without positional tracking may serve as one avenue for analysis. With the assurance of a timestamp value for the images, it becomes plausible to initiate EHLA processes and commence considering the output data.

4.1.2 Real Process Analysis

This section will delve into a comprehensive analysis of an actual process. It involved the utilization of two cameras, one operating at 220 FPS and the other at 520 FPS. The substrate utilized was steel 25CrMo4 with a diameter of 50 mm, with SAE 316L, a stainless steel as a coating material. The plan involved executing 6 trials with a nozzle standoff of 13.5 mm, testing 2 sets of parameters outlined in Table 1. Table 2 also delineates the number of layers and the parameters employed for each test.

Parameter Set	Laser Power	Process Speed	Feed Rate	Shielding Gas Flow	Powder Feed Rate
1	8594 W	98.97 m/min	0.14 mm/rev	11 l/min	54.28 g/min
2	7022 W	71.68 m/min	0.44 mm/rev	11 l/min	64.74 g/min

Table 1 – Sets of parameters used

Experiment Number	Parameter Set	Layers
1 and 2	1	1
3	1	5
4	2	1
5	2	5
6	2	10

Table 2 – Final Test Description

In experiment 1, a portion of the previous weld area received marking using a overhead projector pen, spanning approximately 40° to 80°, to assess its detectability in the images. Additionally, within the same range in experiment 2, a small amount of oil was applied to the surface in order to observe potential variations caused by surface contaminants during the process.

The component underwent laser marking at two points, positioned at 0° and 50°. Additionally, a laser mark was applied in each experiment, starting from the initiation of the cladding process and extending 15 mm in the Z + direction, as well as 40° (equivalent to 17.45 mm of the perimeter) in the C + direction. These markings were implemented to facilitate subsequent analysis and integration with metallography results. The illustrated part is depicted in Figure 24.

Figure 24 – Welding results

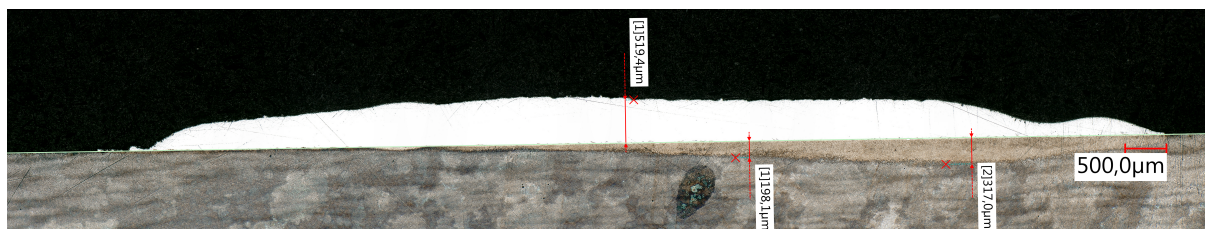
Source: Own (2024) and Fraunhofer ILT (2024).

4.1.2.1 Post-processing

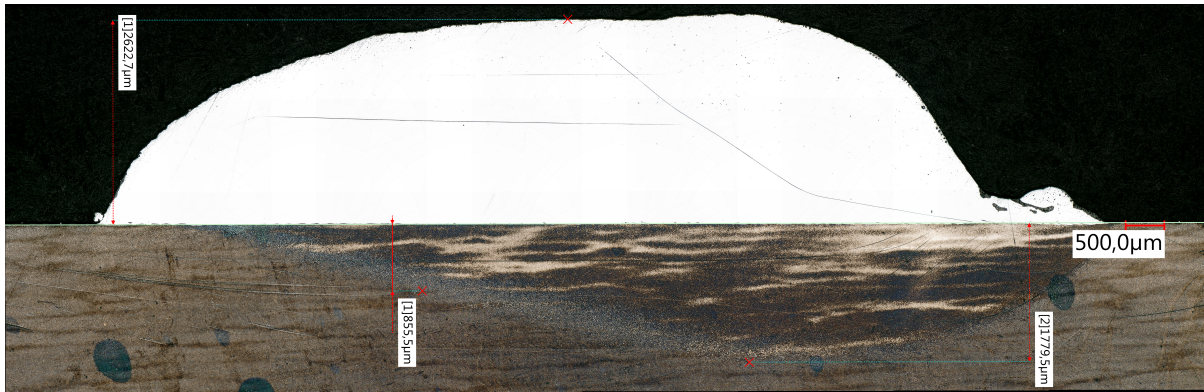
This section of the chapter presents the results of post-processing in metallography, accompanied by the data output from the program.

4.1.2.1.1 Metallography

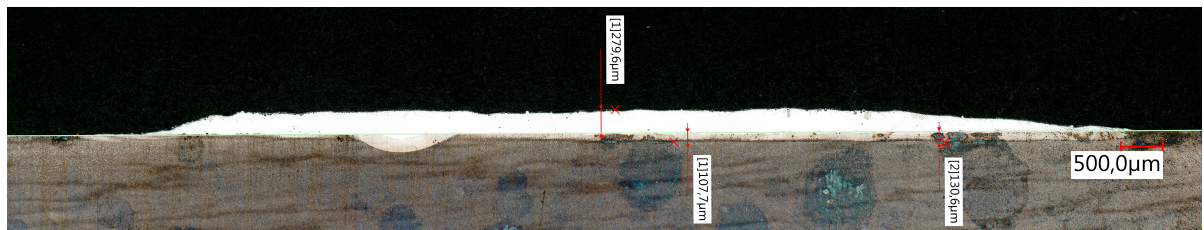
The samples underwent metallographic preparation, with the parts physically marked for reference. A cross-section approximately oriented at 0° was prepared for examination across all experiments. Following cutting, embedding, and polishing, an etching process was performed using HNO_3 to enhance visibility of the heat-affected zone. This acid selectively consumes the steel part of the sample while preserving the added material due to its properties, as represented in Figures 25, 26, 27 and 28. Experiments 1 and 6 can be viewed in Annex B.

Figure 25 – Metallography experiment 2 at 0° 

Source: Fraunhofer ILT (2024).

Figure 26 – Metallography experiment 3 at 0°

Source: Fraunhofer ILT (2024).

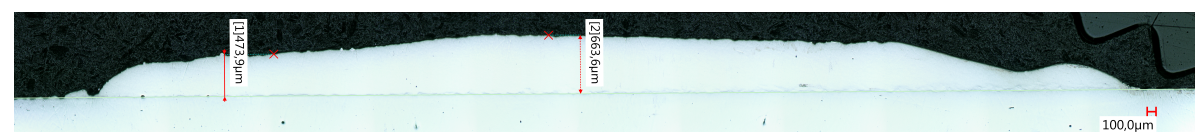
Figure 27 – Metallography experiment 4 at 0°

Source: Fraunhofer ILT (2024).

Figure 28 – Metallography experiment 5 at 0°

Source: Fraunhofer ILT (2024).

Also, in experiment 2, to examine if the oil could provoke some failure in the structure, another cross section was made at 50°, corresponding to one point where the oil was applied (See Figure 29). This time, no etch was used because the focus is to see bounding defects and other features in the structure.

Figure 29 – Metallography Experiment 2 at 50°

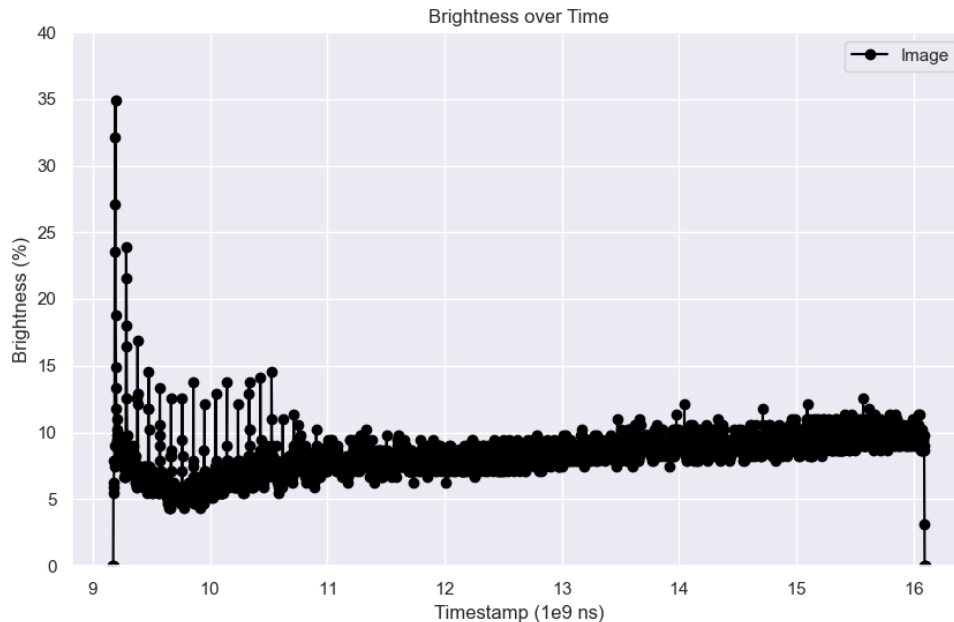
Source: Fraunhofer ILT (2024).

4.1.2.1.2 Data Generated Analysis

Considering that both cameras capture the identical visual perspective, this chapter will emphasize the results obtained from camera 520 FPS, as it boasts the highest frame rate and thus potentially contains more comprehensive information. Additionally, special attention will be dedicated to post-processing techniques, particularly focusing on brightness enhancement, as it allows for a holistic visualization of the image, encompassing the melt pool, tail, gas evaporation, and other pertinent features. However, it's important to note that all generated data is readily available for visualization in the Annex B .

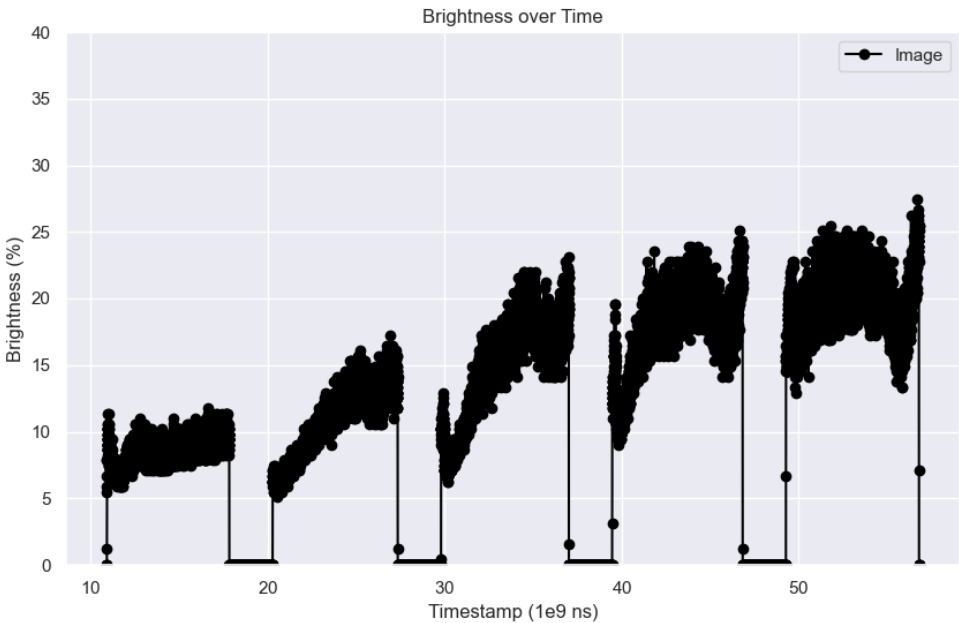
The results of the experiments 2, 3, 4, and 5 (See Figures 30, 31, 32 and 33, respectively). The results from experiment omitted are already integrated within other experiments, differing only in the number of layers. The brightness is represented as a percentage of the entire image, calculated by summing all pixel values and dividing by the total number of pixels, then converted to a percentage. Also, each graph displays several black points, each representing an image within the dataset.

Figure 30 – Brightness Experiment 2



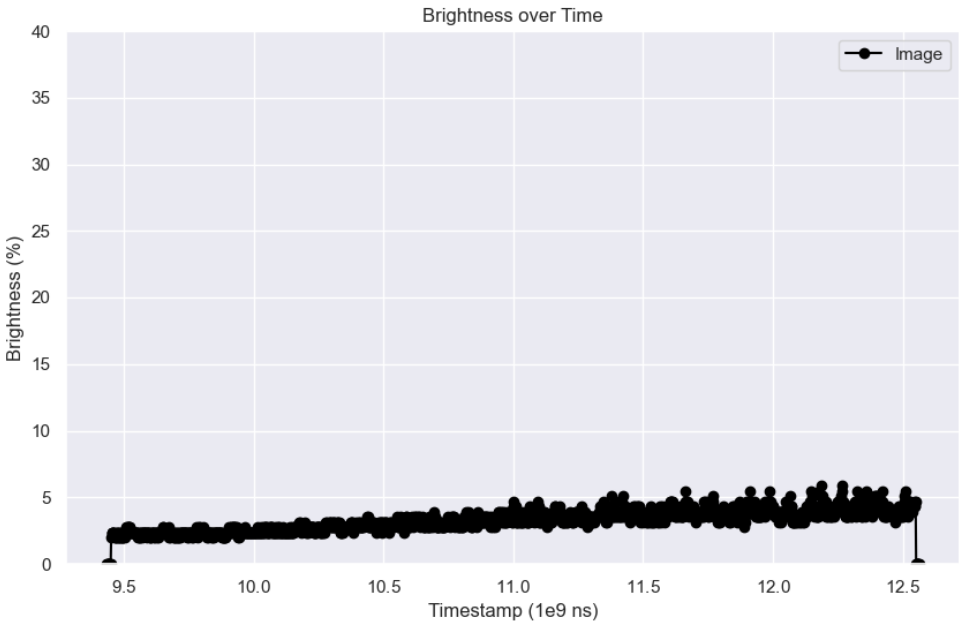
Source: Fraunhofer ILT (2024).

Figure 31 – Brightness Experiment 3

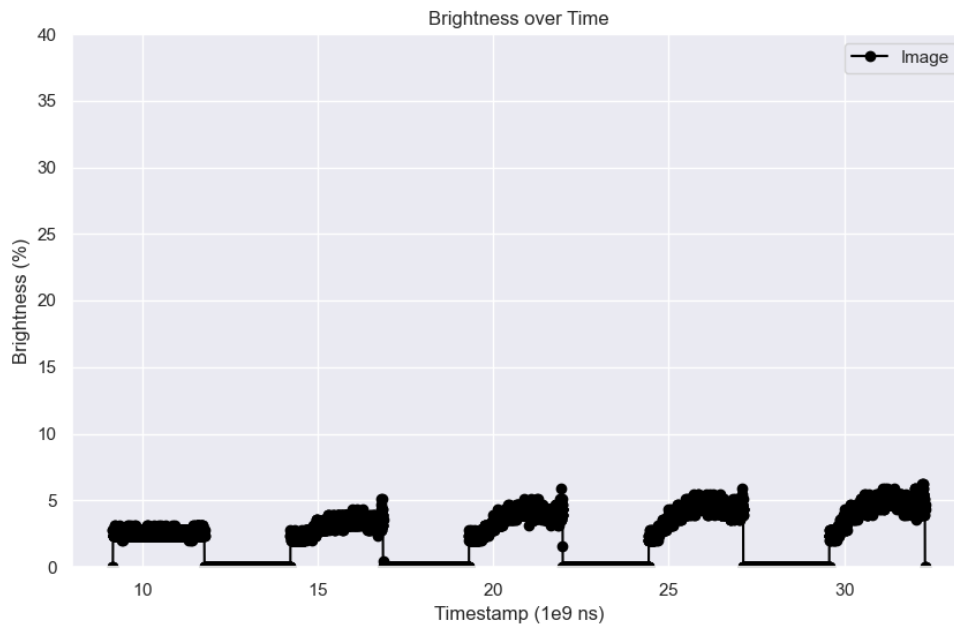


Source: Fraunhofer ILT (2024).

Figure 32 – Brightness Experiment 4



Source: Fraunhofer ILT (2024).

Figure 33 – Brightness Experiment 5

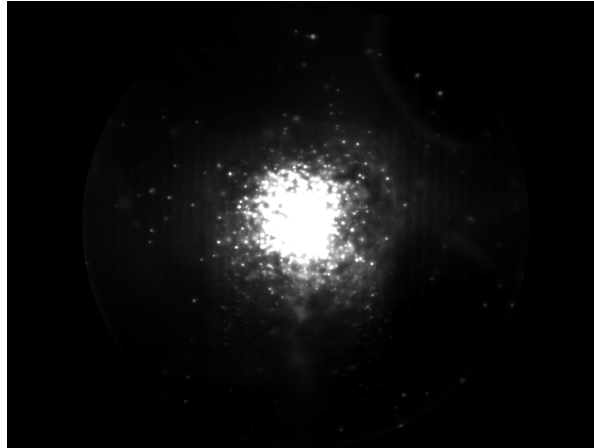
Source: Fraunhofer ILT (2024).

4.2 Analysis and discussion of results

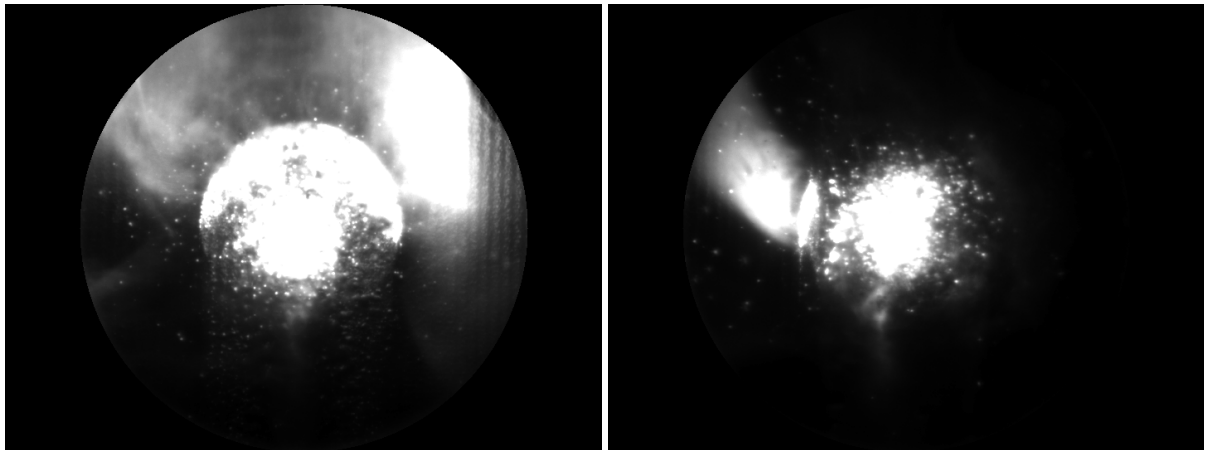
Now, the discussion will focus on the results.

4.2.1 Experiment 1

In Experiment 1, initial expectations centered on the possibility of flaws arising from pen marks. However, upon conducting a comprehensive analysis of the images and data (refer to Annex C), only a limited number of instances revealed any discernible influence from the ink. Figure 34 presents an image capturing the process just prior to the tube passing through the ink coordinates. Furthermore, Figure 35 displays specific images corresponding to a time interval between 9.271 s and 10.322 s. In the preceding image, on the left illustrates the initial light peak, marking the first instance of ink refraction, while the image on the right portrays the final instance of light presence. Following interaction with the laser, the mark diminishes to the point of nearly being undetectable, indicative of heightened heat due to the laser's power. It is plausible that the pencil ink evaporated subsequent to this initial exposure, as no further traces were discernible in the output data or in subsequent metallographic examinations.

Figure 34 – Experiment 1 image at 9.269 s

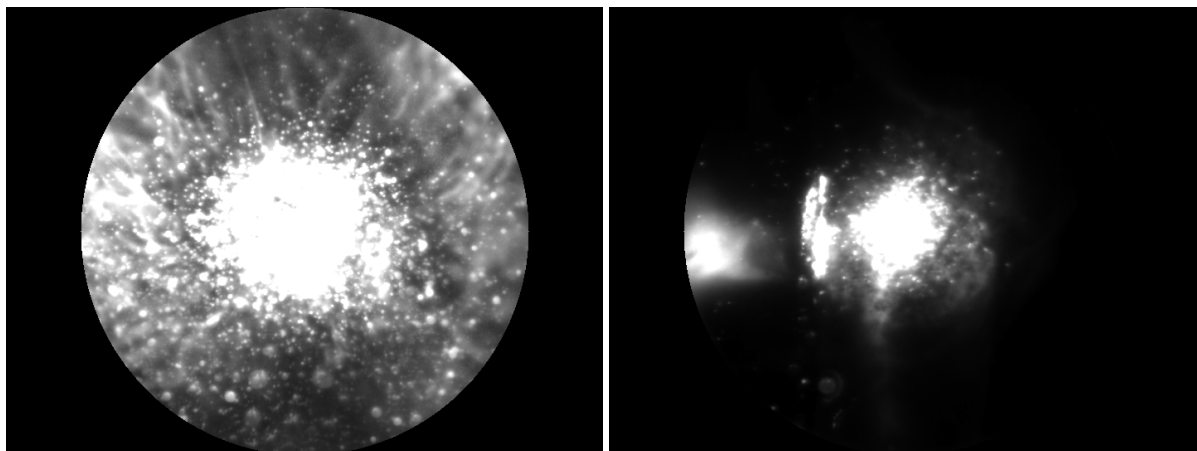
Source: Fraunhofer ILT (2024).

Figure 35 – Experiment 1 images at 9.271 s and 10.322 s

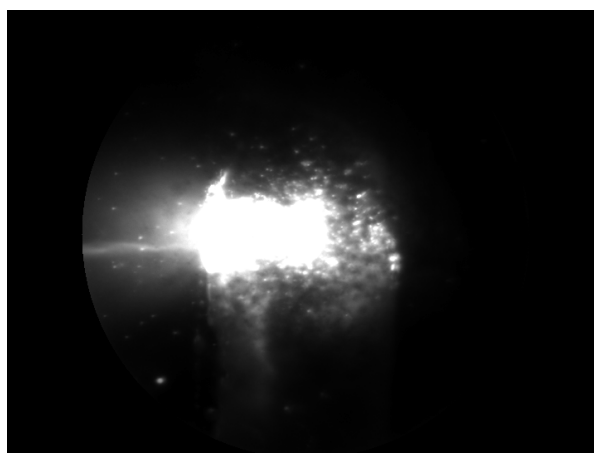
Source: Fraunhofer ILT (2024).

4.2.2 Experiment 2

In experiment 2, the impact of the oil on luminosity was evident. These high levels of luminosity were observed mainly during the initial rotations, decreasing after the twenty-first rotation. Towards the end, some anomalous values appeared, but it is not certain that they are attributable to the application of oil. Figure 36 illustrates oil evaporation at 9.190 s and 11.477 s, showing traces of oil evaporation mainly during the initial interval, and also, an outlier represented in Figure 37 near the end of the experiment.

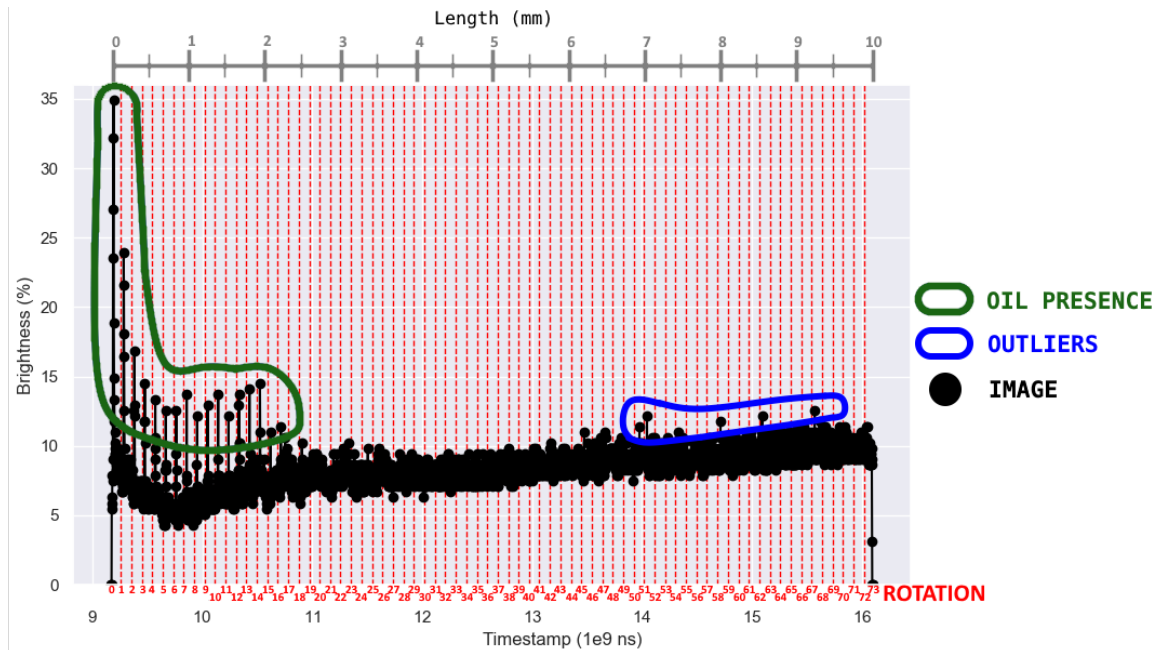
Figure 36 – Oil sparkle at 9.190 s and 11.477 s

Source: Fraunhofer ILT (2024).

Figure 37 – Outlier image at 14.049 s

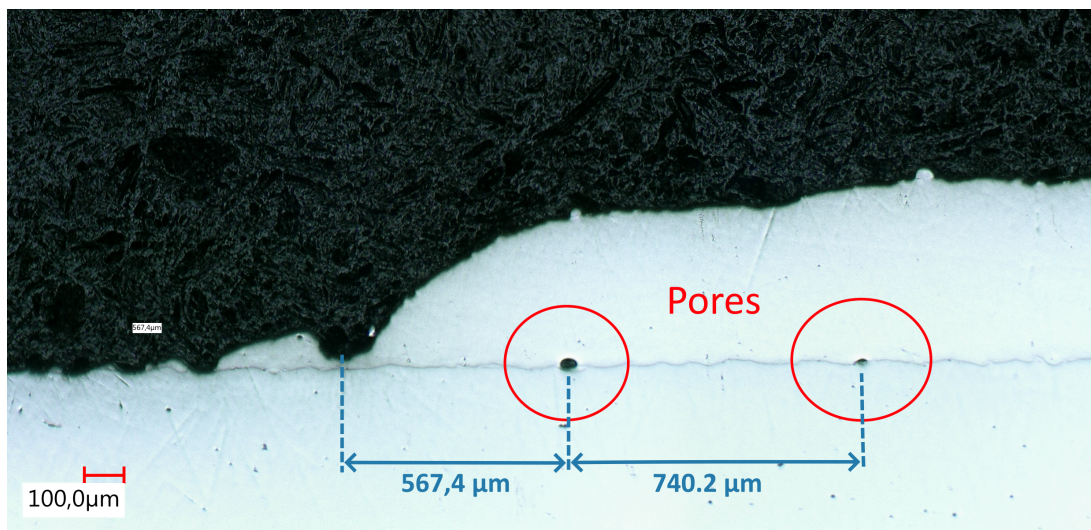
Source: Fraunhofer ILT (2024).

Within moments of initiating the laser, the intense heat rapidly induces the evaporation of the majority of the oil. In Figure 38 at each 0° of the rotation was delineated a red stippled line, and also added a number to the rotation to enhance visibility, also the length between the Z axis was allocated at the top.

Figure 38 – Detailed Experiment 2

Own (2024) and Fraunhofer ILT (2024).

Due to the impact of the oil at the onset of this experiment, a metallography analysis was performed at 50°, with the microscopic findings presented in Figure 39. The examination suggests that the oil may have induced the formation of two pores within the section, as illustrated in Figure 39.

Figure 39 – Pores Experiment 2

Source: Own (2024) and Fraunhofer ILT (2024).

4.2.3 Experiment 3

While the experiment 1 and 2 with 1 layer had one appearance, when it had multiple layers the process manifested a burnt look. This enhances the indication of

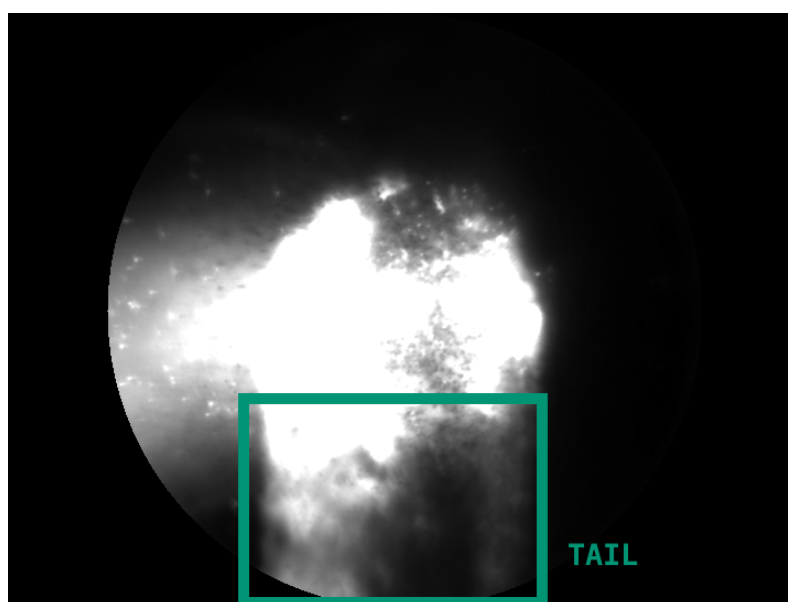
an overabundance of heat in the process. The reference to excessive heat doesn't solely pertain to the excessive laser's power, it could also signify insufficient powder flow or inadequate shielding gas flow. It remains uncertain which factor exerts a greater influence, but it's acknowledged that each of them contributes partially to the outcome.

Upon examining the metallography, review in Figure 26, an irregular heat-affected zone emerges. Analysis of the output data showcasing the area and brightness, reveals a consistent upward trajectory layer by layer, and the transitions between layers is evident by the decreasing of the total brightness of the image.

Area and brightness considerably increased their values (See Annex C), meaning an increase in the temperature of the process. The circularity between layers, becoming to decrease his value in the firsts layers, indicating that the melt pool is losing its shape. This can be attributed to the process operating per revolution of the part, leading to the formation of the liquid metal and, with a tangential force, causes this melt pool to shift slightly in the opposite direction of rotation, creating a tail.

When the material hasn't properly solidified, these tails tend to be larger than usual. In this test, the tail could almost have completed a full round in the tube, considering that the tube has 50 mm diameter, it has an extension of approximately 150 mm. The tail formed is depicted in Figure 40.

Figure 40 – Experiment 3 at the fifth layer



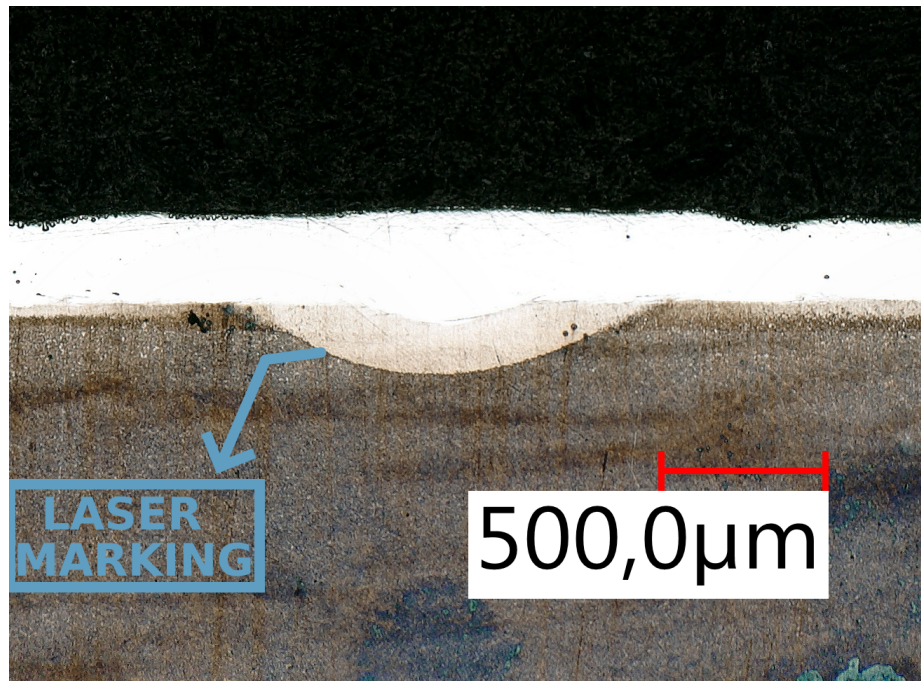
Source: Own (2024) and Fraunhofer ILT (2024).

4.2.4 Experiment 4

In Experiment 4, the Heat Affected Zone (HAZ) also displays an increase in size across the cladding layers, culminating in a larger value at the end, measuring $130.6\ \mu\text{m}$ (Review Figure 27). It's reasonable to say that the laser demarcations may

contribute to the pronounced interference observed in the HAZ (Review Figure 41). However, it's intriguing that the laser markings are more prominent in this test with a single layer for parameter 2. In Experiments 1 and 2, this marking wasn't discernible. One possible reason for this difference could be the thickness of the layer in this experiment, which measures 279 μm (Review Figure 27), compared to Experiment 2, where the thickness is 519.4 μm (Review Figure 25).

Figure 41 – Experiment 4 with laser marking



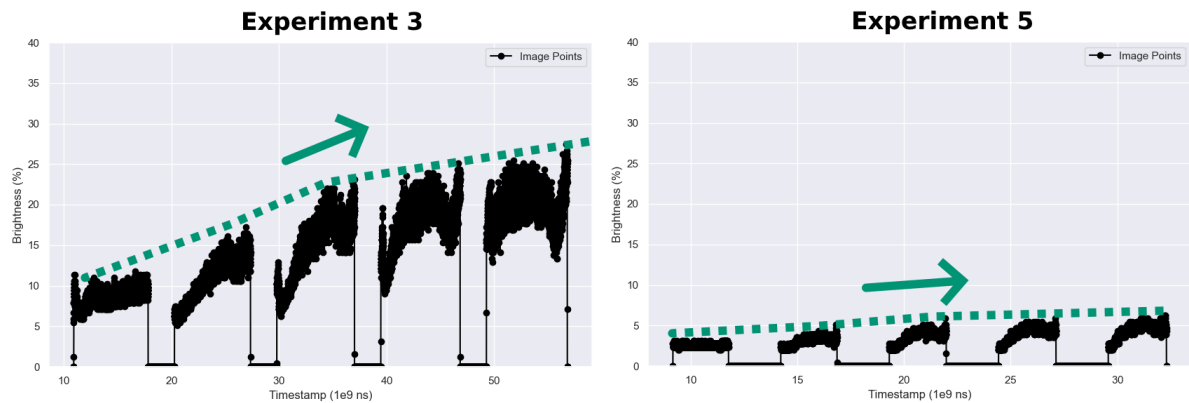
Source: Own (2024) and Fraunhofer ILT (2024).

Analysis of the output data (Annex C) reveals some increasing variation in all the graphs, and appears to be more stable in the end. But this stability is not conclusive, a longer cladding could reveal this characteristic. It prompts further investigation into Experiment 5, which employs these same parameters across 5 layers.

4.2.5 Experiment 5

In Experiment 5, it is advantageous to compare it with Experiment 3, which also consists of 5 layers. Experiment 5 demonstrates greater stability compared to Experiment 3, as illustrated in the brightness graphs (Figure 42). The brightness variation in Experiment 5 ranges from approximately 3% to 7%, whereas in Experiment 3, it fluctuates from 8% to 27%. A similar trend is observed in the area graph, suggesting that parameter 2 holds more promise for achieving a stable cladding.

Figure 42 – Brightness tendency

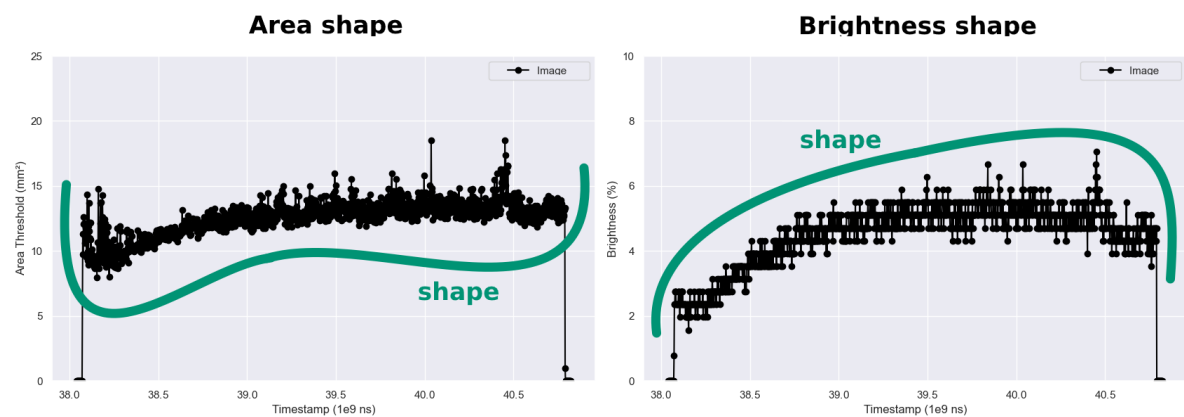


Source: Own (2024) and Fraunhofer ILT (2024).

4.2.6 General Overviews

Upon initially examining the experiment's first layer, the deposition surface appears stable. However, with the introduction of successive layers, the receiving surface becomes influenced by the characteristics of the preceding layer, leading to variations. Upon analyzing the graphs, the area exhibits a shape reminiscent of a "W", while the brightness trend follows a curve resembling an inverted "C". These observations are clarified in Figure 43, depict the Experiment 6 upon closer scrutiny of the sixth layer.

Figure 43 – Brightness tendency

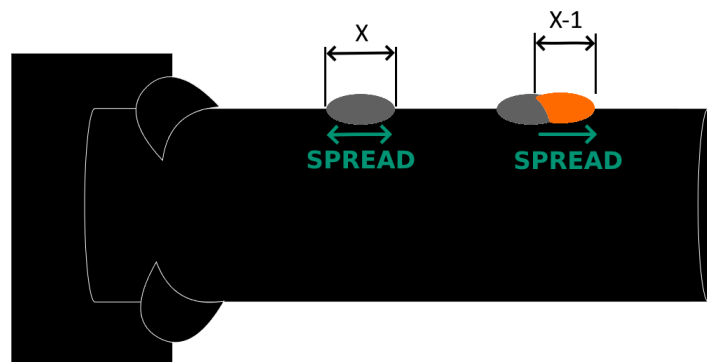


Source: Own (2024) and Fraunhofer ILT (2024).

Area

When the cladding undergoes its initial rotation, the melt pool area reaches its maximum extent. During this phase, the material encounters no obstructions and can naturally spread. However, upon completing the first rotation, the melt pool finds itself confined by the preceding layers of cladding. Consequently, its expansion is restricted primarily to the side against the cladding, as depicted in Figure 44. The region marked as 'X' represents the area influenced by the current rotation, while the region labeled 'X-1' denotes the lower area influenced by the preceding rotation.

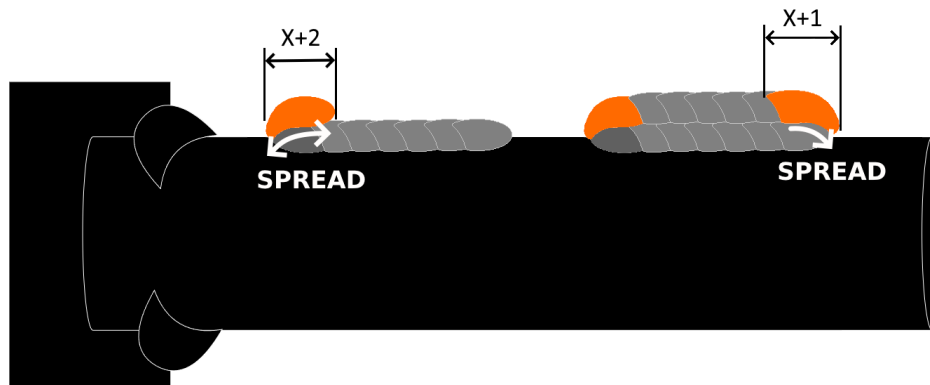
Figure 44 – Area variation first layer



Source: Own (2024) and Fraunhofer ILT (2024).

After the first layer is deposited, the surface of subsequent layers is influenced by the geometry of the previous layer. Consequently, variations in the deposition surface may increase due to overlapping between successive turns, a contrast to the relatively uniform initial surface. Furthermore, as the cladding process continues, the deposited material accumulates thickness. Along the outer edges, lacking lateral support from adjacent layers, the molten material tends to spread out until solidification occurs. These dynamics are illustrated in Figure 45.

Figure 45 – Area multilayers variation

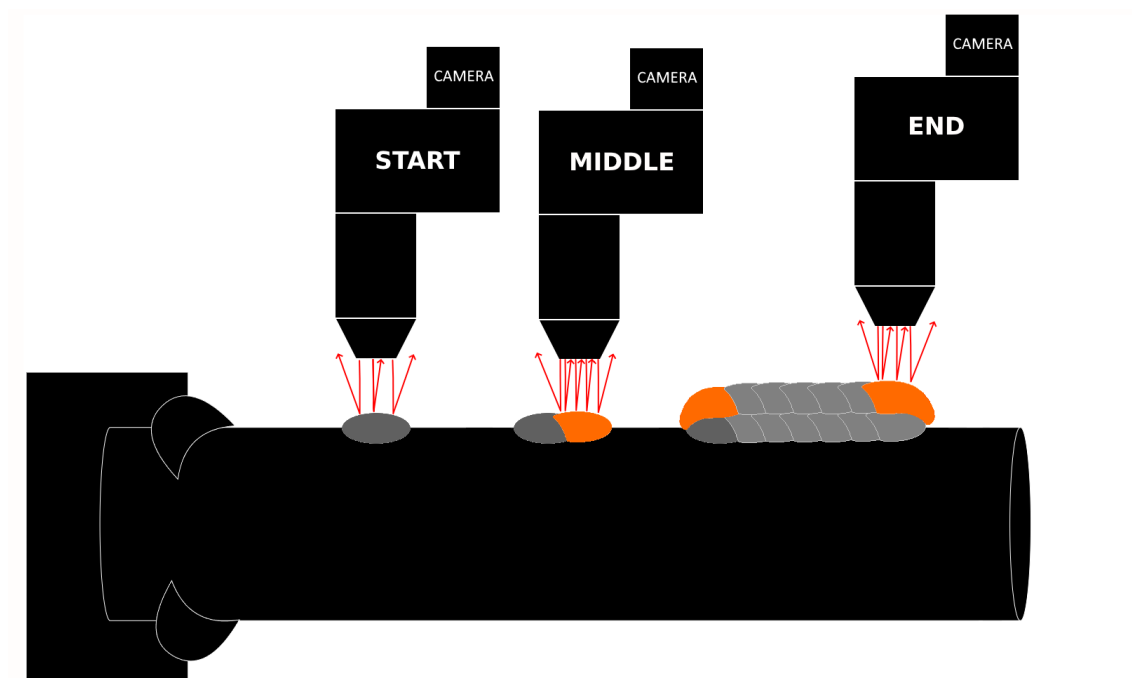


Source: Own (2024) and Fraunhofer ILT (2024).

Brightness

The brightness captured in images reflects the melt pool's characteristics and evolves with each process stage. Understanding how the waveform refracts through the nozzle is crucial. In the middle of the process, the laser optic system captures heightened brightness as waveform refracts more towards the cameras from the top of the pool. However, as the pool extends towards the edges, its geometry distorts, causing waveform dispersion and a reduction in brightness. These concepts are visually depicted in Figure 46, illustrating brightness variations from start to midpoint and ultimately to completion.

Figure 46 – Brightness variation



Source: Own (2024) and Fraunhofer ILT (2024).

5 CONSIDERATIONS AND OUTLOOK

The evolution of manufacturing processes, marked by the emergence of Extreme High-Speed Laser Metal Deposition (EHLA), underscores the critical need for sophisticated tools for data acquisition and analysis. Despite facing numerous developmental challenges, this technology is steadily maturing, yet remains partially uncharted. Nonetheless, its immense promise is evident, with novel approaches driving its adoption and relevance in the current industrial landscape, poised for widespread application.

Given the absence of specialized software for EHLA, the primary objective of this thesis was to develop a software that integrates industrial cameras and CNC controllers to elevate process monitoring and optimization. Through the acquisition of synchronized images, its aim was to glean insights into the intricacies of the process, delineating features within images, such as the melt pool area, circularity and image brightness. However, the accurate interpretation of these graphical data hinges on the researcher's expertise, similar to fine-tuning parameters to yield optimal results aligned with requirements.

At all, the analysis of output data yields insights into the process, aiding for parameter development. Also, through the program and analysis, variations resulting from contaminant influences on the substrate surface was successfully identified, thereby creating opportunities for industrial applications in quality assurance. With this achievements, the thesis satisfactorily fulfills its objectives

Next Steps

Enhanced output data analysis and feature extraction from images stand out as areas ripe for further exploration, ensuring the continual advancement of the program. As image analysis remains pivotal, ongoing efforts to augment the software's capabilities will unlock new dimensions in process optimization and understanding.

BIBLIOGRAPHY

- BASLER. *Basler Machine Vision Experte | Basler AG*. 2024. Available at <https://www.baslerweb.com/de-de/>. Accessed in February 2024. 22, 24, 26
- BUSCHMANN, D. *et al.* Data-driven decision support for process quality improvements. In: . [S.l.]: Elsevier B.V., 2021. v. 99, p. 313–318. ISSN 22128271. 14, 15
- CLAMIR. *Clamir: Specifications*. 2024. Available at <https://www.clamir.com/specifications/>. Accessed in February 2024. 23
- DESHPANDE, P. Metamorphic detection using function call graph analysis. 10 2013. Available at https://scholarworks.sjsu.edu/etd_projects/336. Accessed in March 2024. 25
- FANUC. *FANUC: Focas Development Libraries*. 2024. Available at <https://www.fanuc.eu/de/de/cnc/development-software/focas-development-libraries>. Accessed in February 2024. 26
- FRAUNHOFER. *PATENT ILT EHLA - Extreme High Speed Laser Deposition Welding Method*. 2012. DE 10 2011 100 456 A1, 2012.11.08. 5, 6
- FRAUNHOFER, I. *Fraunhofer ILT - Ihr Partner für Innovationen*. 2024. Available at <https://www.ilt.fraunhofer.de/>. Accessed in March 2024. 33
- FREDERIC, G.; VOORT, V. *Metallography of Welds*. 2019. Available at <https://www.researchgate.net/publication/285808596>. Accessed in March 2024. 15, 20, 21, 64
- GITLAB. *GitLab official website*. 2024. Available at <https://about.gitlab.com/>. Accessed in February 2024. 25
- GRAF, R. F. Modern dictionary of electronics. In: GRAF, R. F. (Ed.). *Modern Dictionary of Electronics (Seventh Edition)*. Seventh edition. Boston: Newnes, 1999. p. 1–51. ISBN 978-0-08-051198-6. Available at <https://www.sciencedirect.com/science/article/pii/B9780080511986500060>. Accessed in March 2024. 25
- GTV VERSCHLEIBSCHUTZ, G. *GTV: Powder Feeders and Feeding Systems*. 2024. Available at <https://www.gtv-mbh.de/en/equipment-technology/feeding-systems.html>. Accessed in February 2024. 20
- HORNET. *Standard Systems | Hornet Laser Cladding*. 2024. Available at <https://www.hornetlasercladding.com/standard-systems>. Accessed in February 2024. 20, 24
- KEYENCE GERMANY, G. *Keyence: Automation and quality assurance solutions*. 2024. Available at <https://www.keyence.de/>. Accessed in February 2024. 64
- METPREP, L. *MetPrep: Metallurgical and Petrographic laboratories*. 2024. Available at <https://metprep.co.uk/>. Accessed in February 2024. 64

MICROSOFT. *Microsoft official website*. 2024. Available at <https://www.microsoft.com/de-de/>. Accessed in February 2024. 25

MOHIDEEN, R. M. K.; PETER, P.; WEICKERT, J. A systematic evaluation of coding strategies for sparse binary images. *Signal Processing: Image Communication*, Elsevier B.V., v. 99, 11 2021. ISSN 09235965. 30

OCYLOK, S. *et al.* Correlations of melt pool geometry and process parameters during laser metal deposition by coaxial process monitoring. In: . [S.l.]: Elsevier B.V., 2014. v. 56, p. 228–238. ISSN 18753892. 21, 22

OPENCV. *OpenCV - Open Computer Vision Library*. 2024. Available at <https://opencv.org/>. Accessed in February 2024. 26

PAHL, G. *et al.* *Engineering Design: A Systematic Approach*. [S.l.: s.n.], 2007. ISBN 978-1-84628-318-5. 14

PASZKE, A. *et al.* Pytorch: An imperative style, high-performance deep learning library. 12 2019. Disponível em: <http://arxiv.org/abs/1912.01703>. 26, 34

PEIRCE, J. W. Psychopy-psychophysics software in python. *Journal of Neuroscience Methods*, v. 162, p. 8–13, 5 2007. ISSN 01650270. 25

SAABITH, A. L. S.; VINOTHRAJ, T.; FAREEZ, M. Popular python libraries and their application domains. *International Journal of Advance Engineering and Research Development*, v. 7, 2020. ISSN 2348-6406. Available at <https://www.researchgate.net/publication/349828209>. Accessed in March 2024. 25

SALONEN, A. *Learn Programming*. 2018. Available at <https://www.dbooks.org/learn-programming-1722834927/>. Accessed in March 2024. 25, 30

SCHOPPHOVEN, T.; GASSER, A.; BACKES, G. Ehla: Extreme high-speed laser material deposition. *Laser Technik Journal*, Wiley, v. 14, p. 26–29, 9 2017. ISSN 1613-7728. 14, 17, 18, 19

SOORI, M.; AREZOO, B.; DASTRES, R. *Internet of things for smart factories in industry 4.0, a review*. [S.l.]: KeAi Communications Co., 2023. 192-204 p. 14

THIELE, M. *et al.* Laser metal deposition controlling: Melt pool temperature and target / actual height difference monitoring. In: . [S.l.]: Elsevier B.V., 2020. v. 94, p. 441–444. ISSN 22128271. 15

TOMASI, J. *et al.* Learned camera gain and exposure control for improved visual feature detection and matching. 2 2021. Disponível em: <http://arxiv.org/abs/2102.04341> <http://dx.doi.org/10.1109/LRA.2021.3058909>. 28

TRUMPF. *Bildverarbeitung für Schneid- und Schweißanwendungen | TRUMPF*. 2024. Available at https://www.trumpf.com/de_DE/produkte/laser/sensorik/bildverarbeitung-schneid-schweissanwendung/. Accessed in February 2024. 20

VAFADAR, A. *et al.* *Advances in metal additive manufacturing: A review of common processes, industrial applications, and current challenges*. [S.l.]: MDPI AG, 2021. 1-33 p. 14, 17

WEMAN, K. *Welding processes handbook*. [S.l.]: Woodhead Pub., 2003. 193 p. ISBN 0849317738. 14

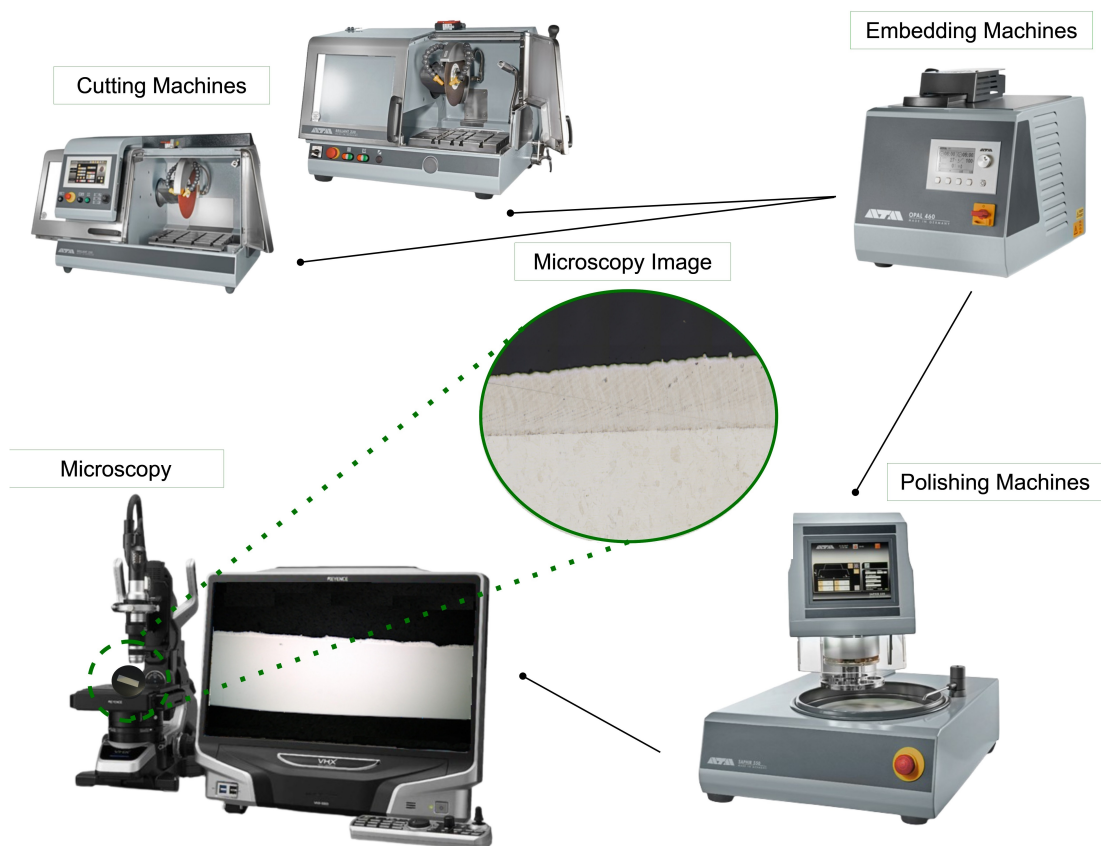
XIRIS. *Xiris WeldStudio™ 3 and WeldStudio™ 3 Pro* | Xiris Automation GmbH. 2024. Available at <https://info.xiris.com/xiris-weldstudio-3-weldstudio-3-pro>. Accessed in February 2024. 23

ANNEX

ANNEX A – METALLOGRAPHY AND MICROSCOPY ILLUSTRATION

Figure 47 depicts the initial machinery employed for cutting, facilitating the creation of cross-sectional views for the part under analysis. During this phase, extraneous portions of the original part, deemed unnecessary, are excised. Subsequently, embedding machines are utilized to enhance management efficiency throughout these procedures, preceding the grinding and polishing processes. It is worth noting that thorough polishing significantly improves the visualization quality of the resultant image (FREDERIC; VOORT, 2019).

Figure 47 – Metallography and Microscopy Image

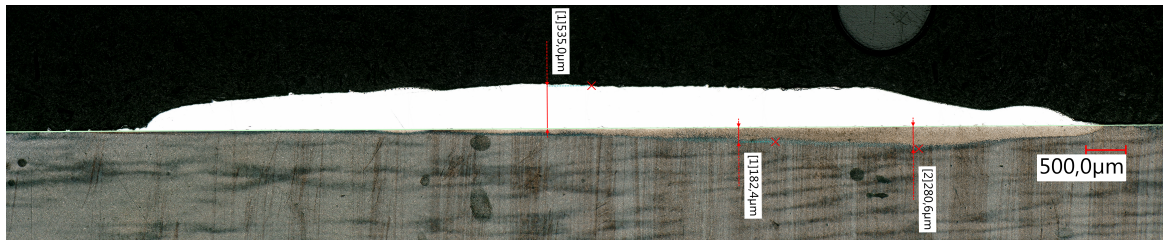


Source: Adapted from Metprep (2024), KEYENCE GERMANY (2024) and Fraunhofer ILT(2024)

ANNEX B – METALLOGRAPHY RESULTS

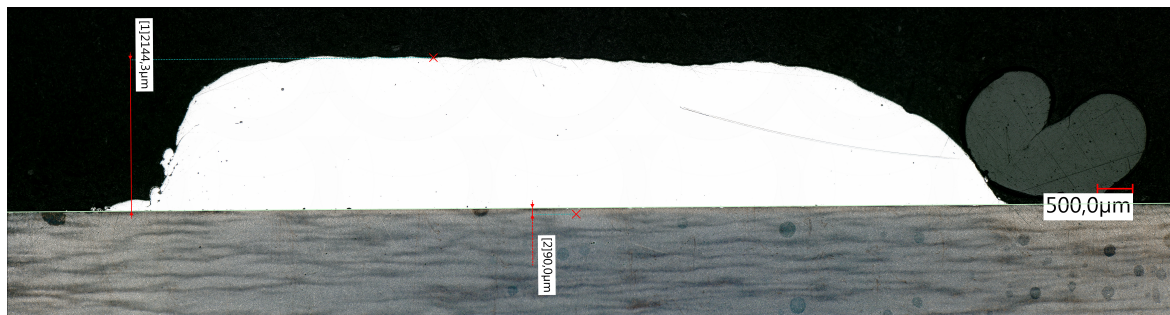
In this annex, two metallography images are provided as supplementary material to the main text. Figures 48 and 49 display the metallography for experiments 1 and 6, respectively.

Figure 48 – Metallography Experiment 1 at 0°



Source: Fraunhofer ILT(2024)

Figure 49 – Metallography Experiment 6 at 0°



Source: Fraunhofer ILT(2024)

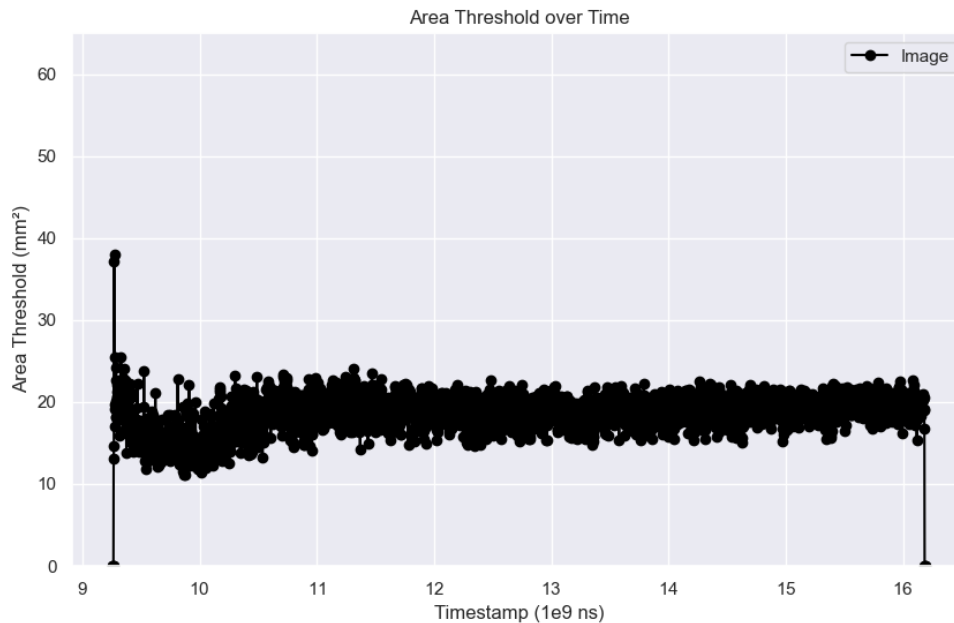
ANNEX C – DATA OUTPUT RESULTS

Here, we offer all the graphs generated from the output data, providing supplementary information for future analysis. The section is divided in each experiment data.

Experiment 1

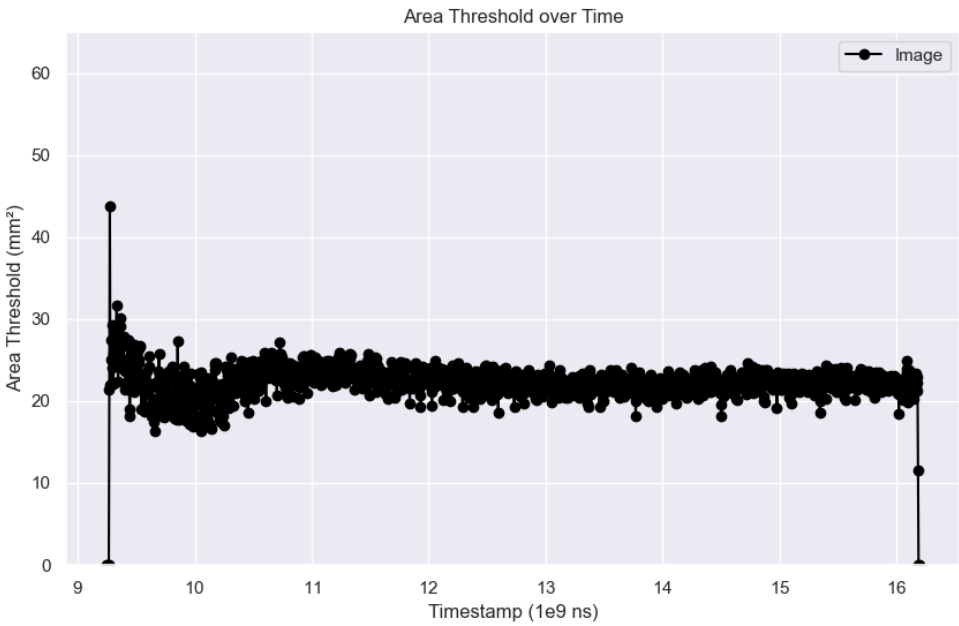
Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 50 and 51, respectively. Subsequently, the brightness distribution is depicted in Figures 52 and 53, following the same order. Additionally, circularity data is illustrated in Figures 54 and 55.

Figure 50 – Area threshold Experiment 1 - Camera 520 FPS



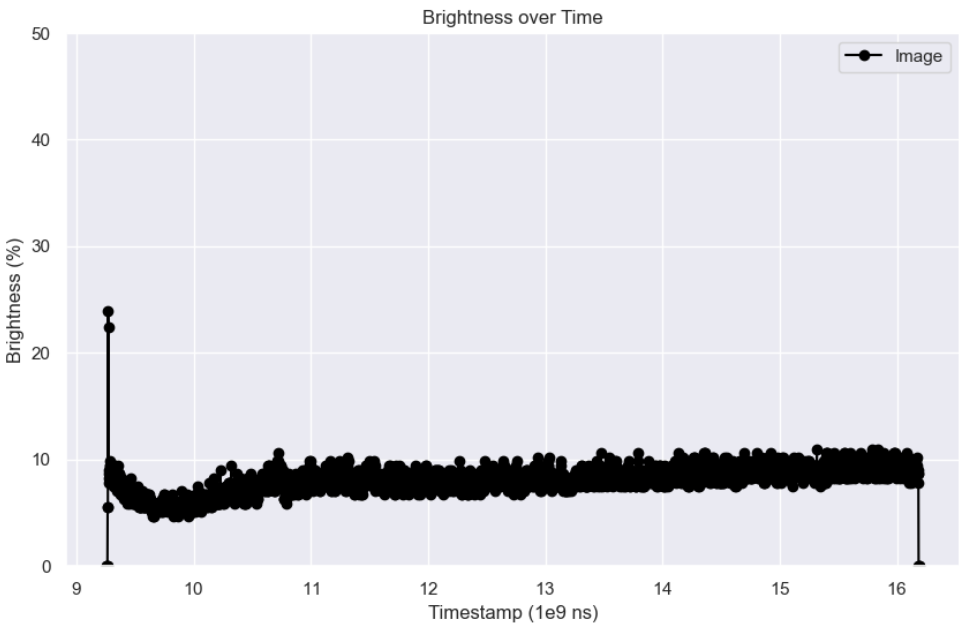
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 51 – Area threshold Experiment 1 - Camera 220 FPS



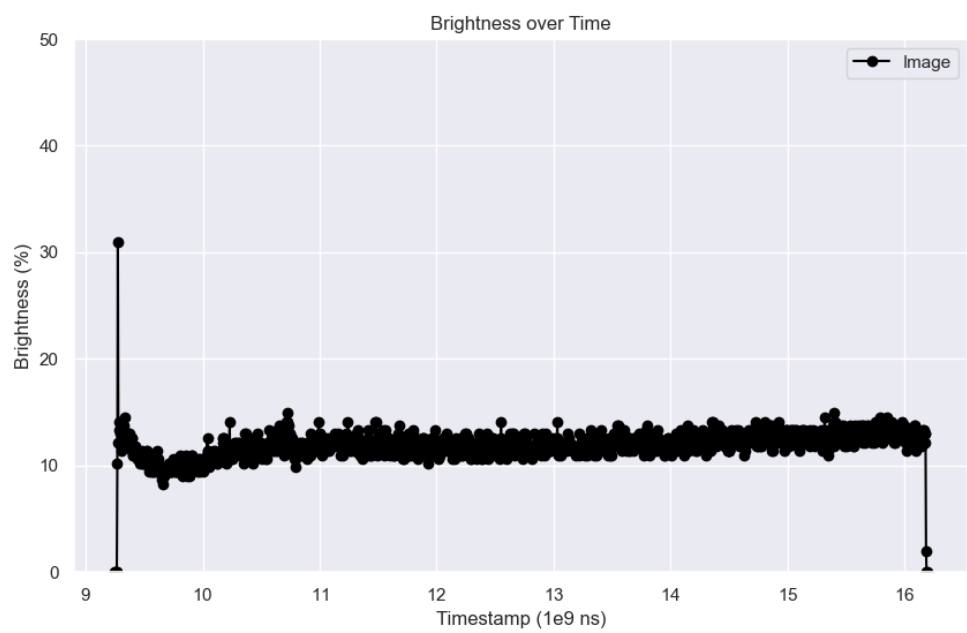
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 52 – Brightness Experiment 1 - Camera 520 FPS



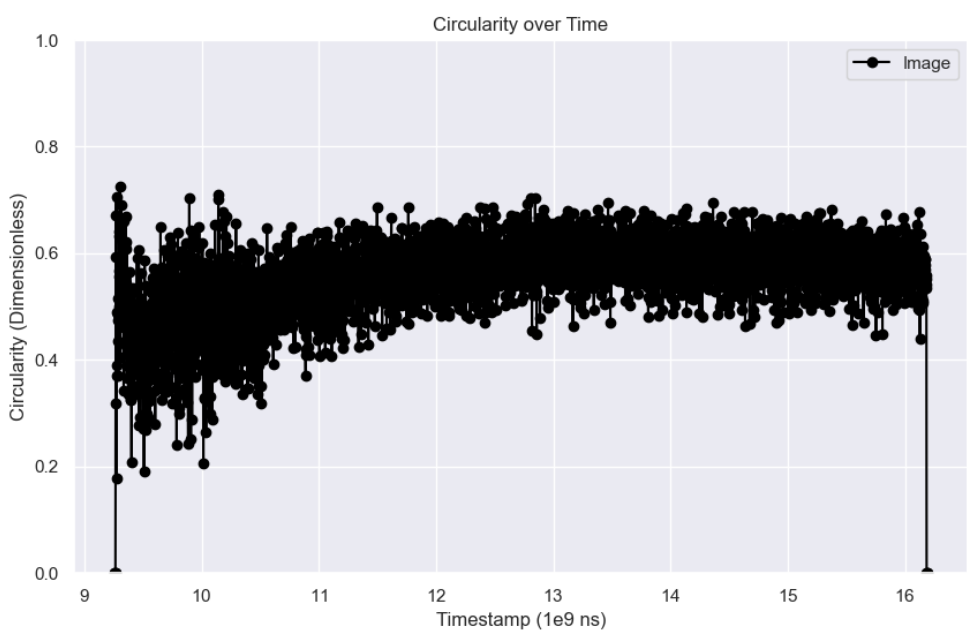
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 53 – Brightness Experiment 1 - Camera 220 FPS

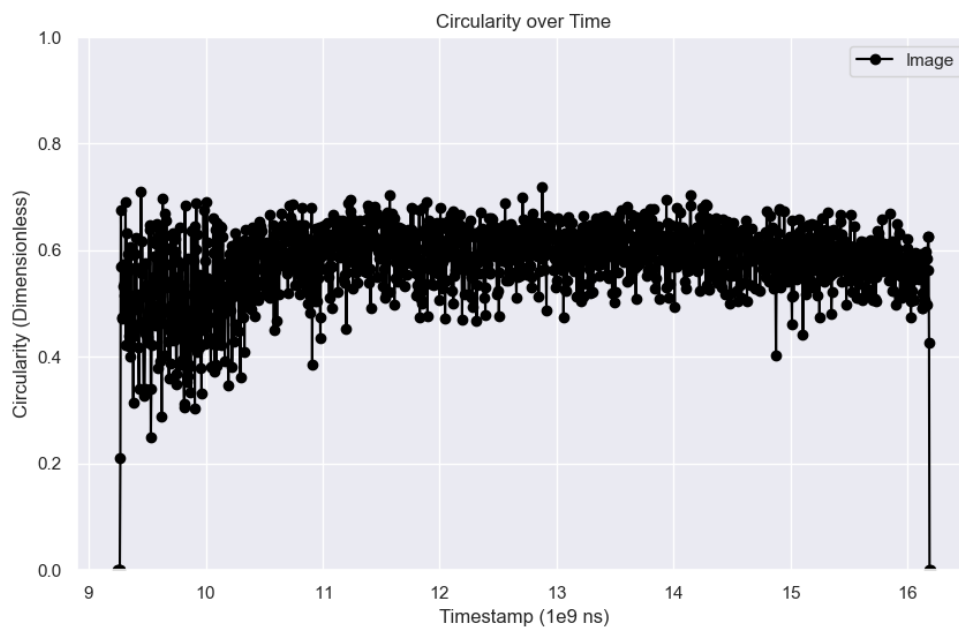


Source: Own (2024) and Fraunhofer ILT (2024)

Figure 54 – Circularity Experiment 1 - Camera 520 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

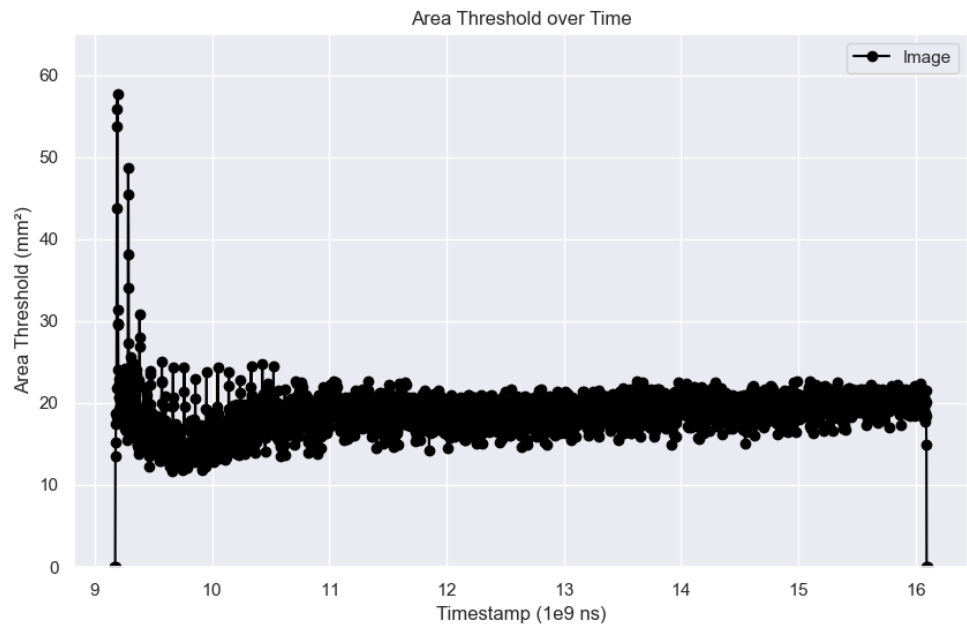
Figure 55 – Circularity Experiment 1 - Camera 220 FPS

Source: Own (2024) and Fraunhofer ILT (2024)

Experiment 2

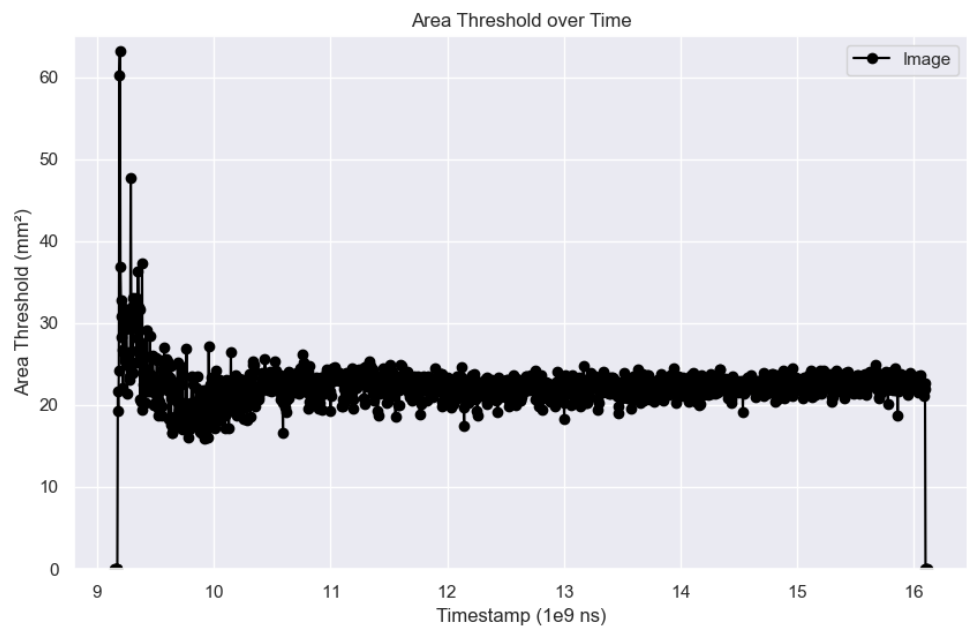
Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 56 and 57, respectively. Subsequently, the brightness distribution is depicted in Figures 58 and 59, following the same order. Additionally, circularity data is illustrated in Figures 60 and 61.

Figure 56 – Area threshold Experiment 2 - Camera 520 FPS



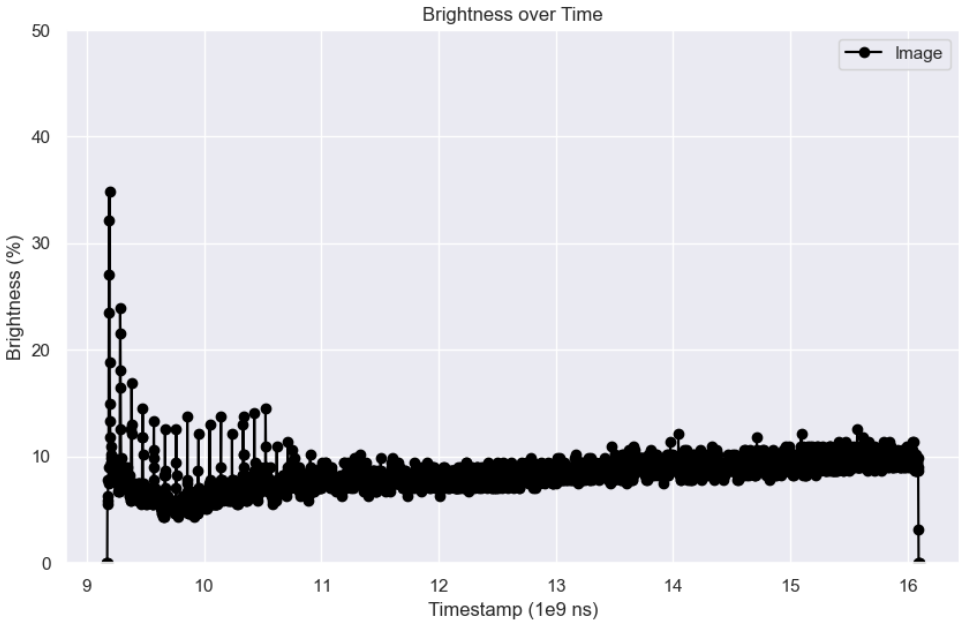
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 57 – Area threshold Experiment 2 - Camera 220 FPS



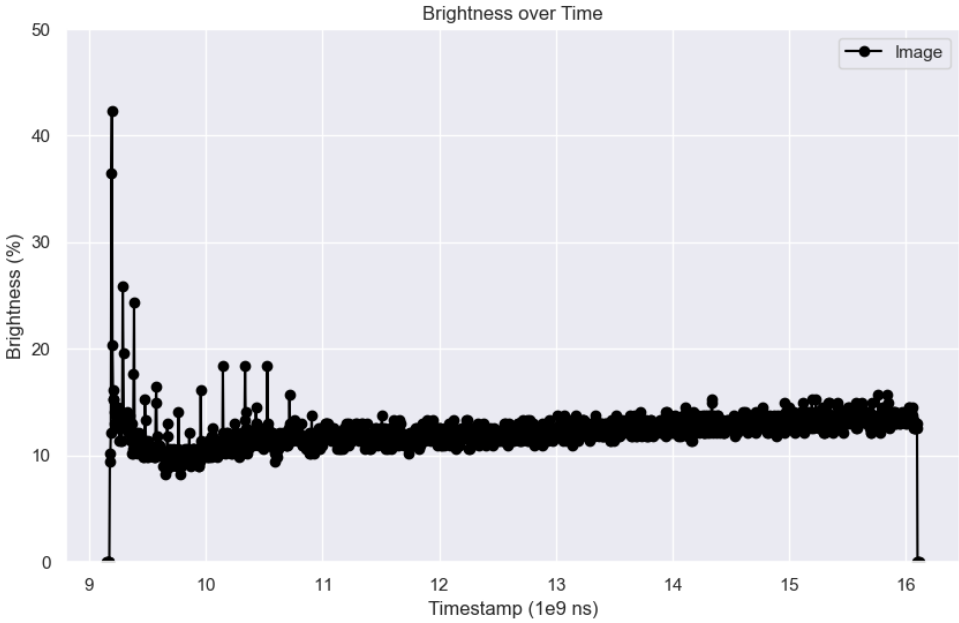
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 58 – Brightness Experiment 2 - Camera 520 FPS

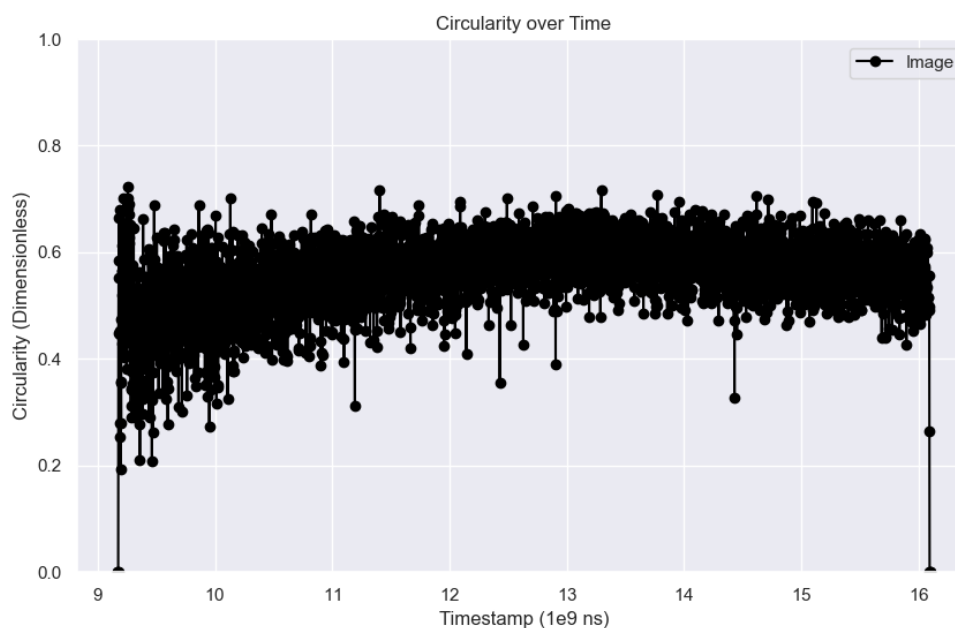


Source: Own (2024) and Fraunhofer ILT (2024)

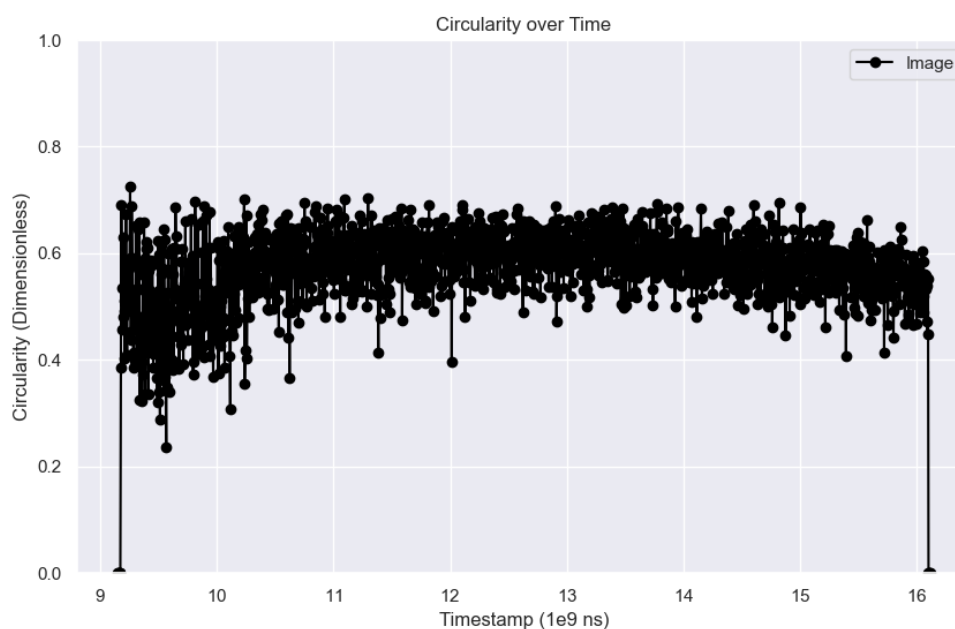
Figure 59 – Brightness Experiment 2 - Camera 220 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

Figure 60 – Circularity Experiment 2 - Camera 520 FPS

Source: Own (2024) and Fraunhofer ILT (2024)

Figure 61 – Circularity Experiment 2 - Camera 220 FPS

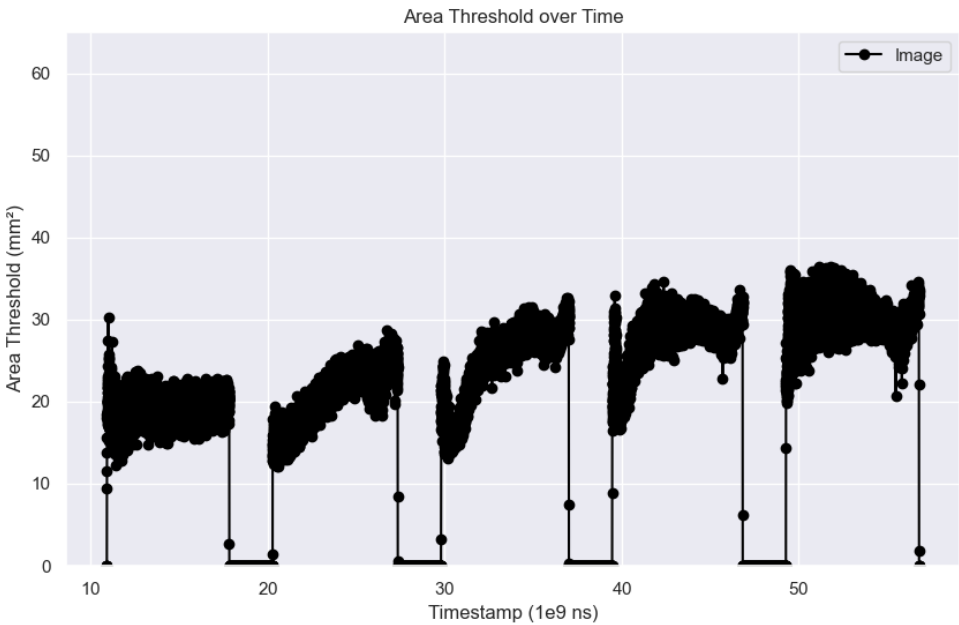
Source: Own (2024) and Fraunhofer ILT (2024)

Experiment 3

Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 62 and 63, respectively. Subsequently, the brightness

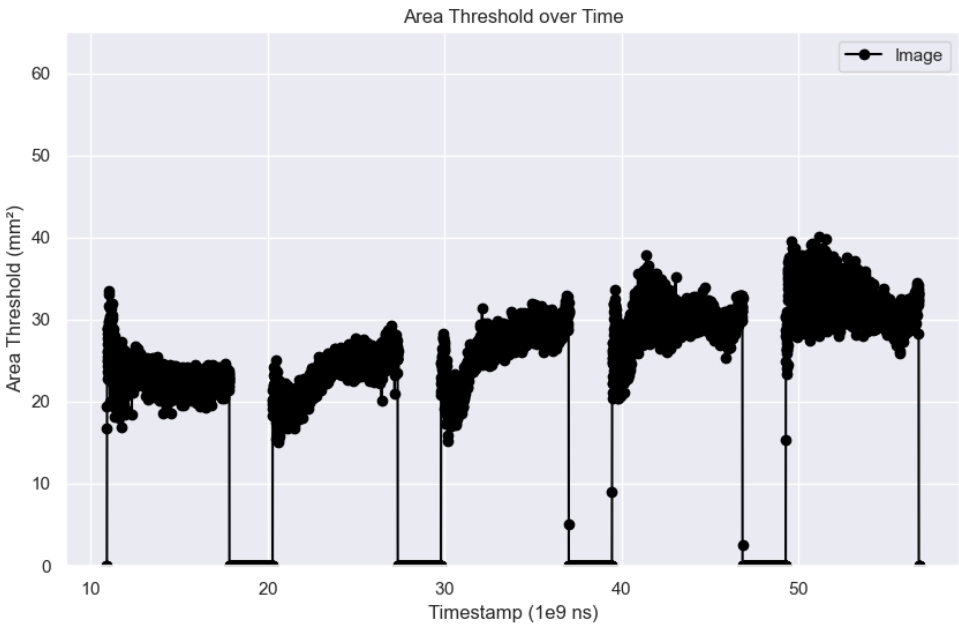
distribution is depicted in Figures 64 and 65, following the same order. Additionally, circularity data is illustrated in Figures 66 and 67.

Figure 62 – Area threshold Experiment 3 - Camera 520 FPS



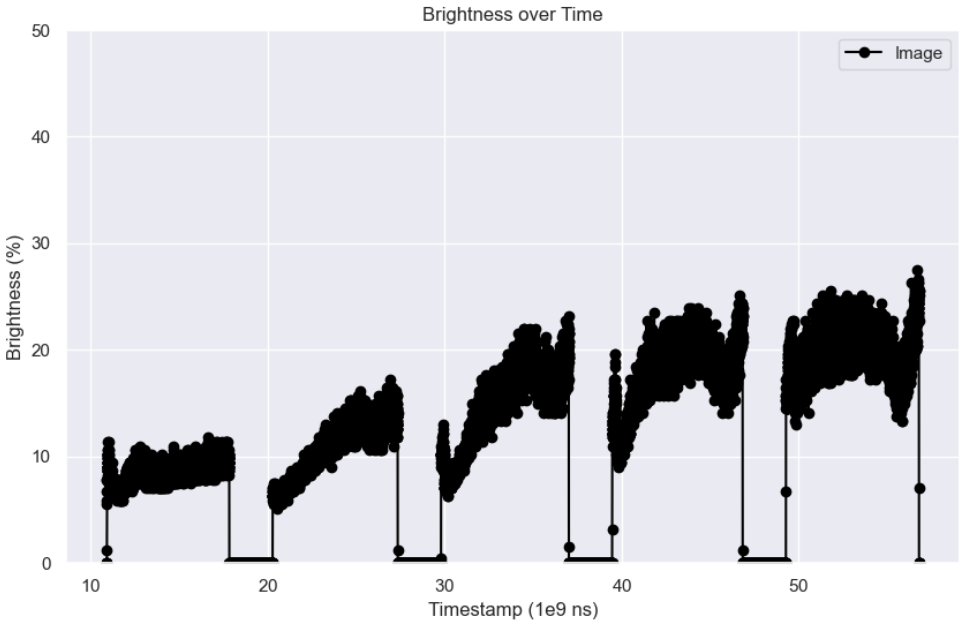
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 63 – Area threshold Experiment 3 - Camera 220 FPS



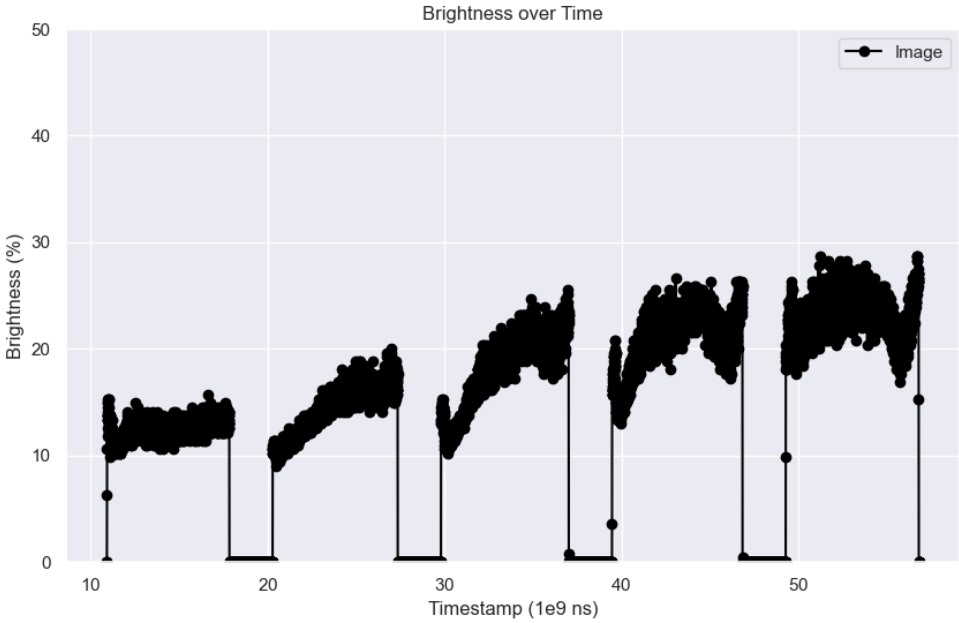
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 64 – Brightness Experiment 3 - Camera 520 FPS

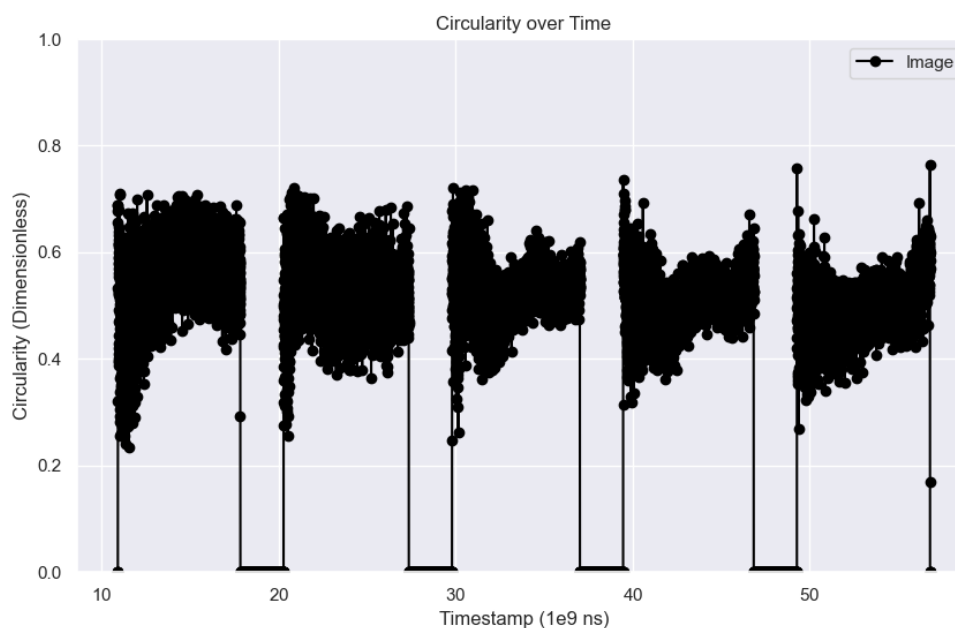


Source: Own (2024) and Fraunhofer ILT (2024)

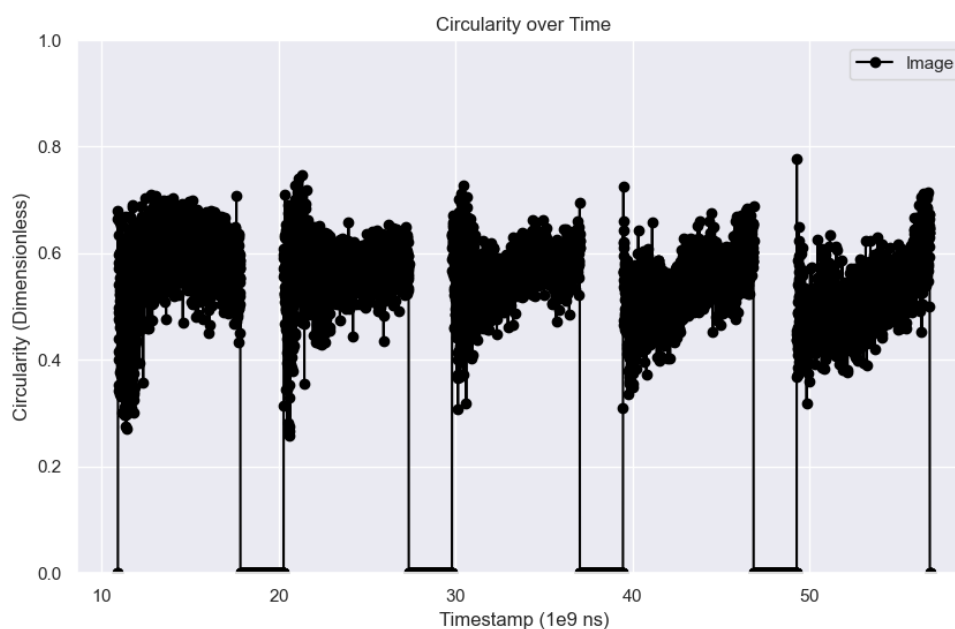
Figure 65 – Brightness Experiment 3 - Camera 220 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

Figure 66 – Circularity Experiment 3 - Camera 520 FPS

Source: Own (2024) and Fraunhofer ILT (2024)

Figure 67 – Circularity Experiment 3 - Camera 220 FPS

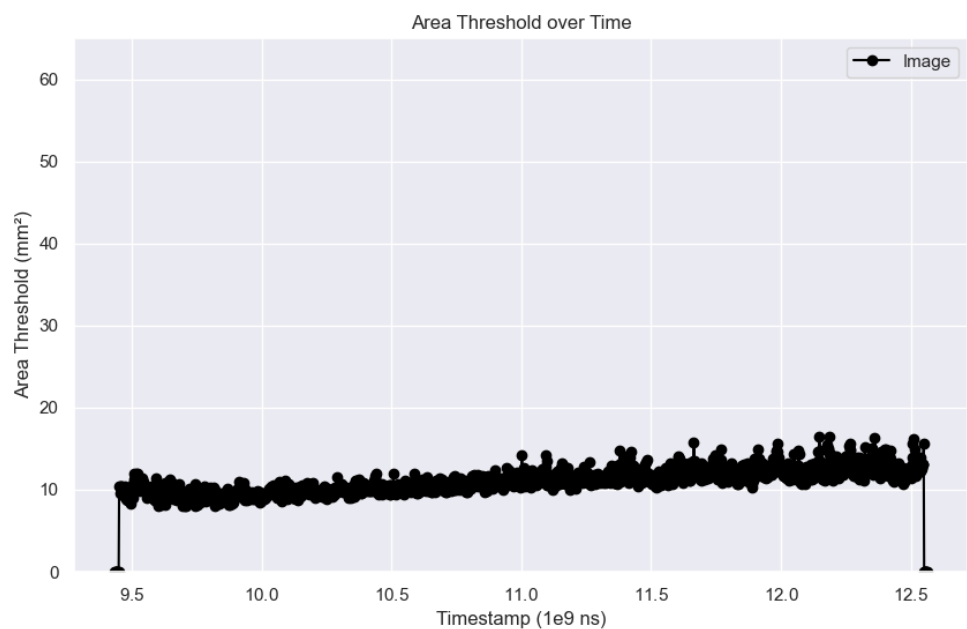
Source: Own (2024) and Fraunhofer ILT (2024)

Experiment 4

Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 68 and 69, respectively. Subsequently, the brightness

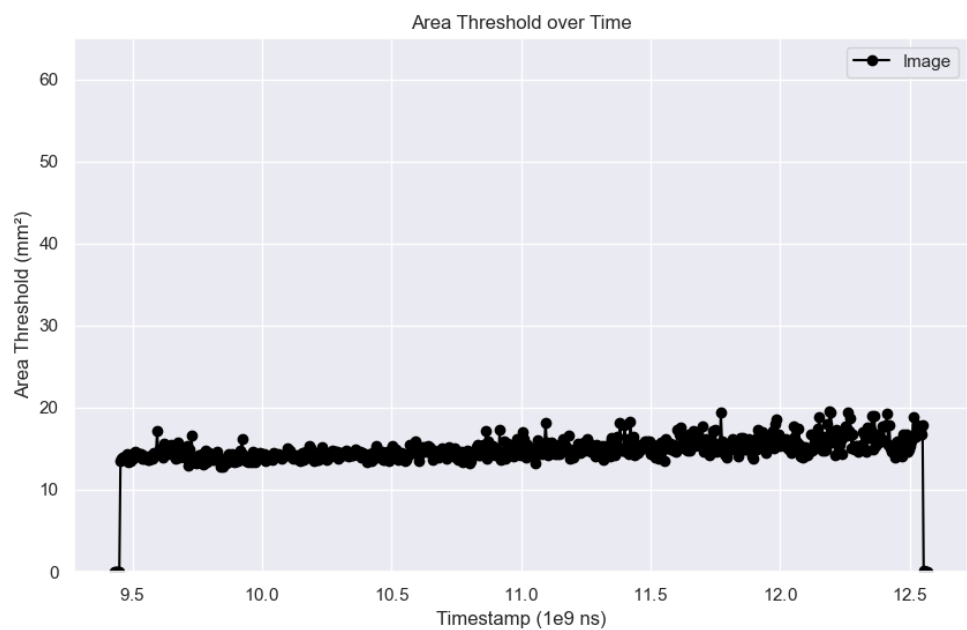
distribution is depicted in Figures 70 and 71, following the same order. Additionally, circularity data is illustrated in Figures 72 and 73.

Figure 68 – Area threshold Experiment 4 - Camera 520 FPS



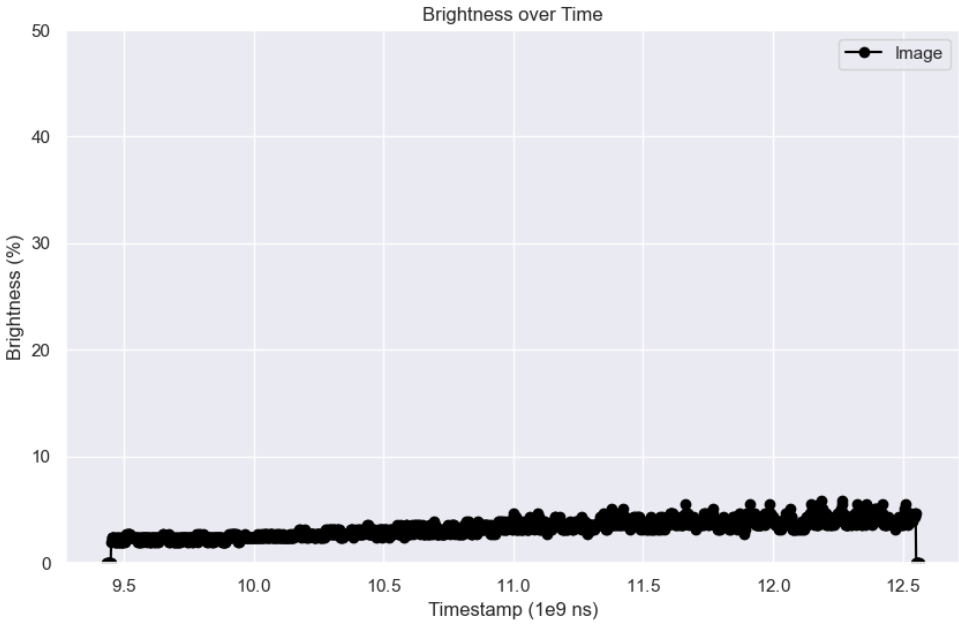
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 69 – Area threshold Experiment 4 - Camera 220 FPS



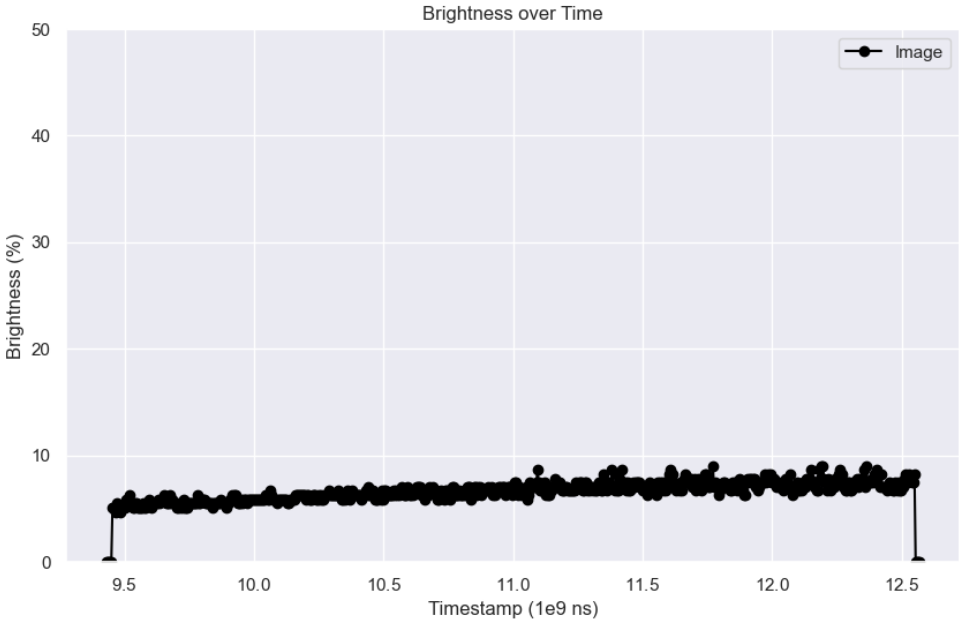
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 70 – Brightness Experiment 4 - Camera 520 FPS

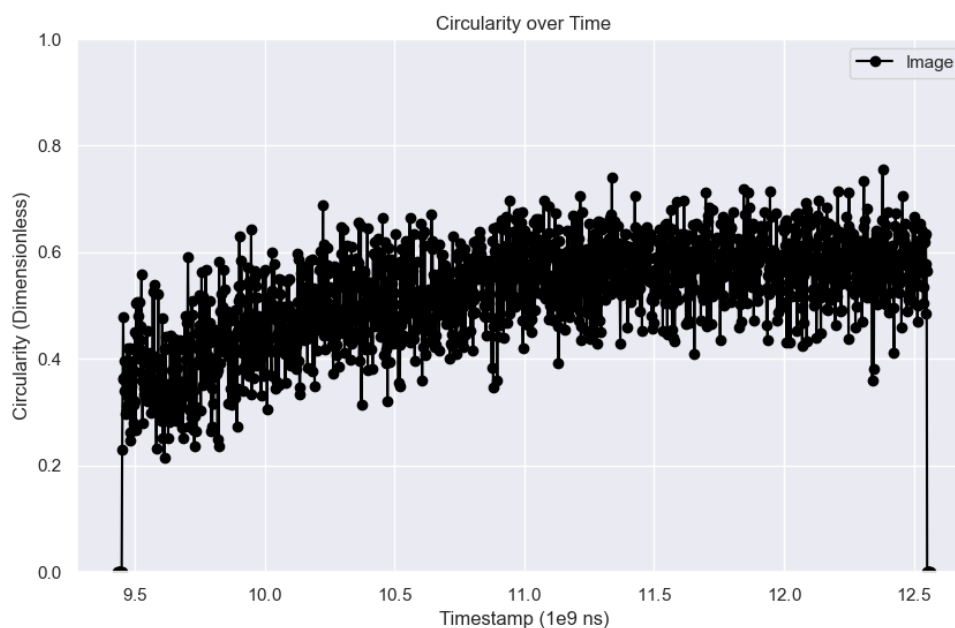


Source: Own (2024) and Fraunhofer ILT (2024)

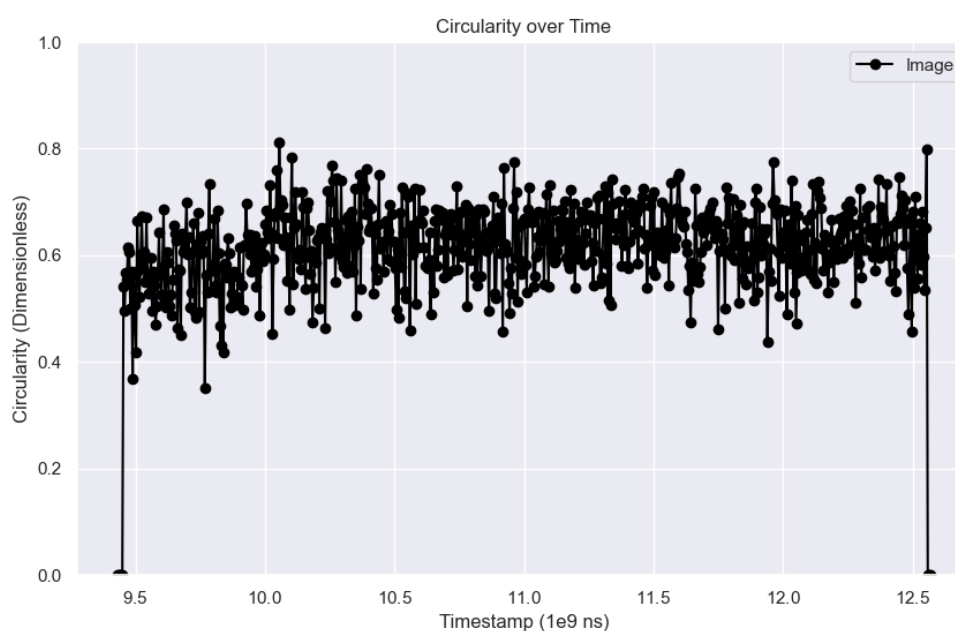
Figure 71 – Brightness Experiment 4 - Camera 220 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

Figure 72 – Circularity Experiment 4 - Camera 520 FPS

Source: Own (2024) and Fraunhofer ILT (2024)

Figure 73 – Circularity Experiment 4 - Camera 220 FPS

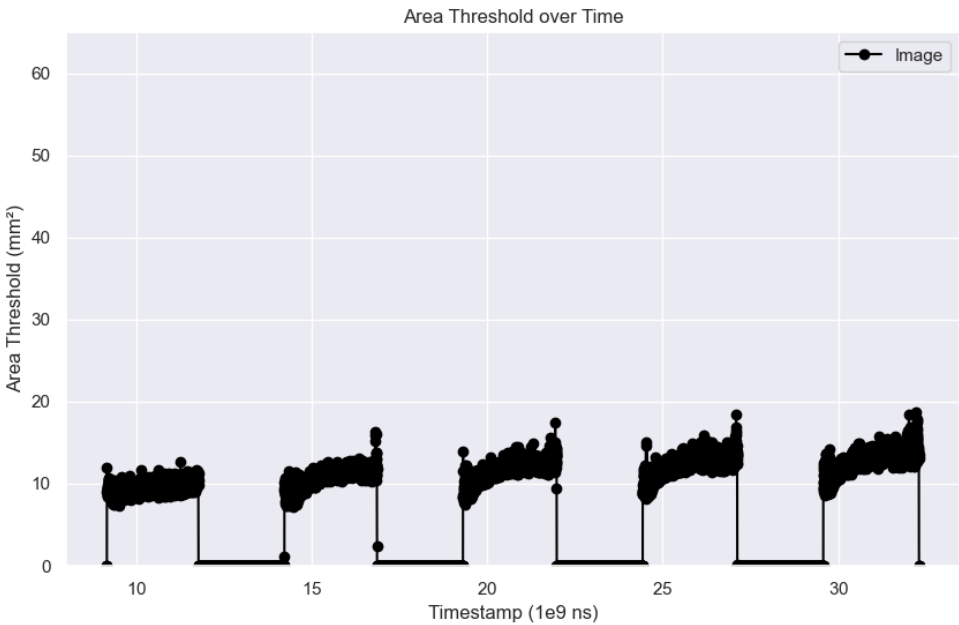
Source: Own (2024) and Fraunhofer ILT (2024)

Experiment 5

Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 74 and 75, respectively. Subsequently, the brightness

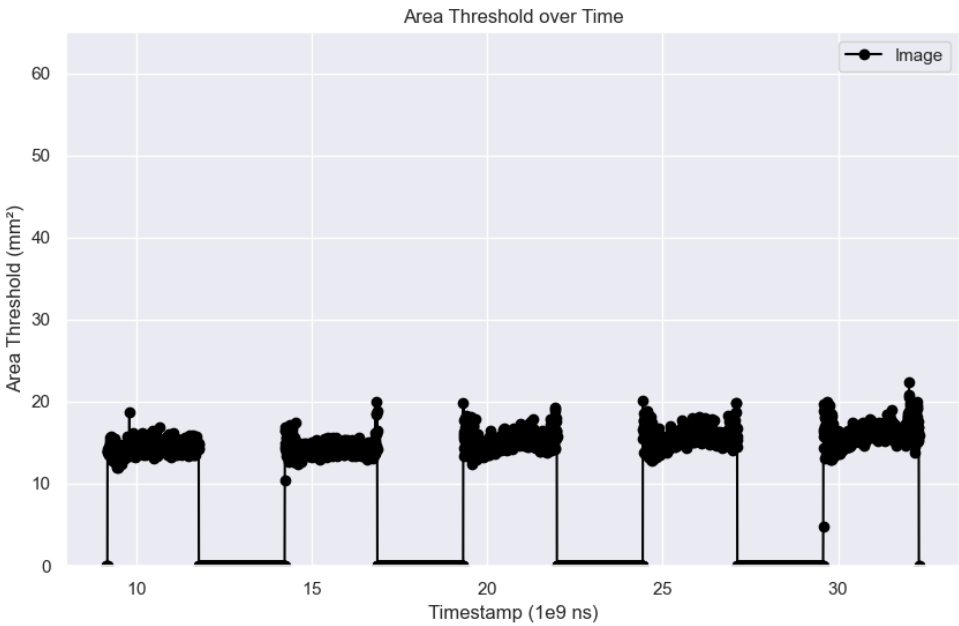
distribution is depicted in Figures 76 and 77, following the same order. Additionally, circularity data is illustrated in Figures 78 and 79.

Figure 74 – Area threshold Experiment 5 - Camera 520 FPS



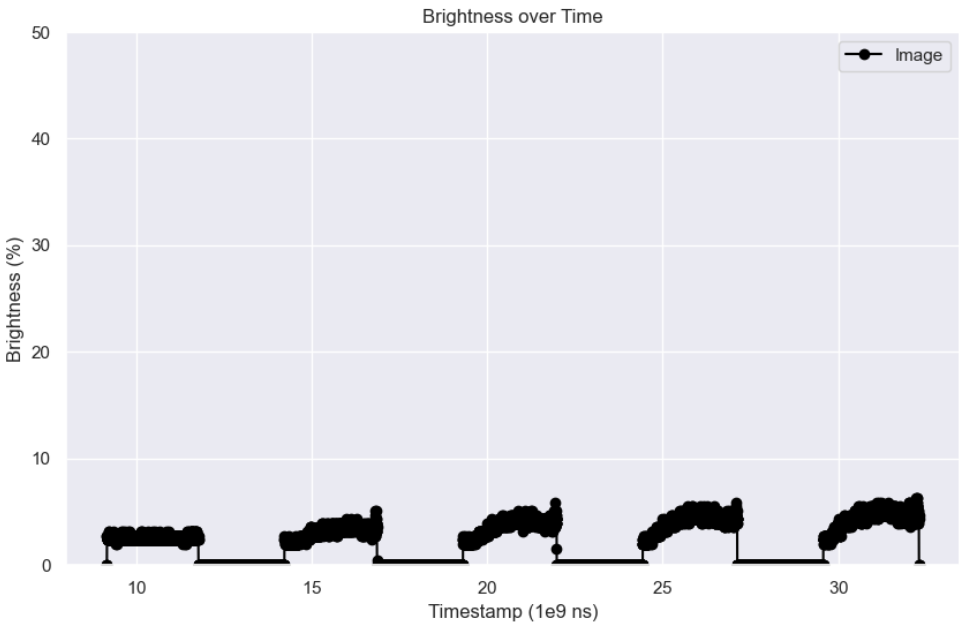
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 75 – Area threshold Experiment 5 - Camera 220 FPS



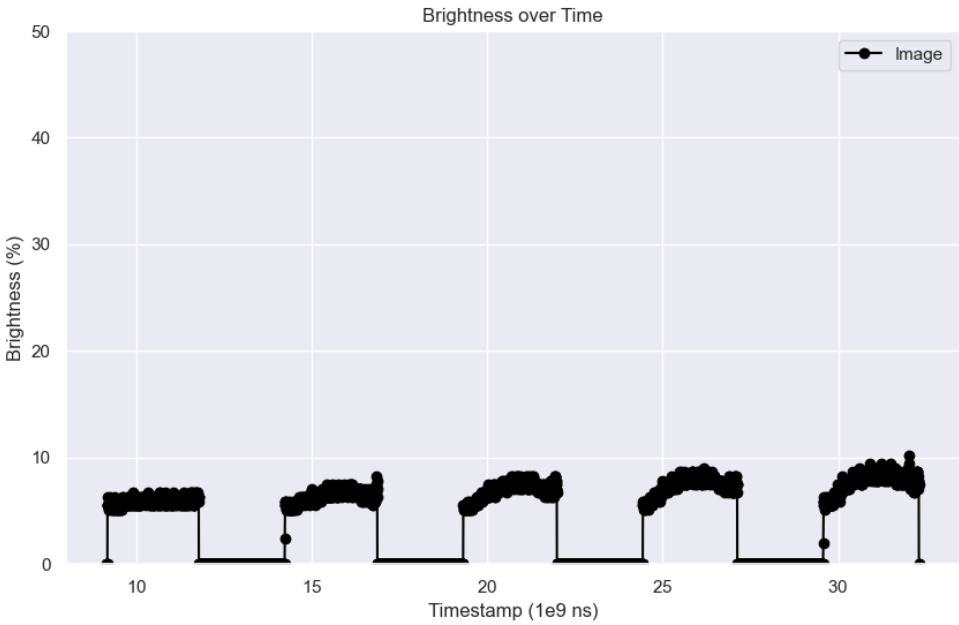
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 76 – Brightness Experiment 5 - Camera 520 FPS

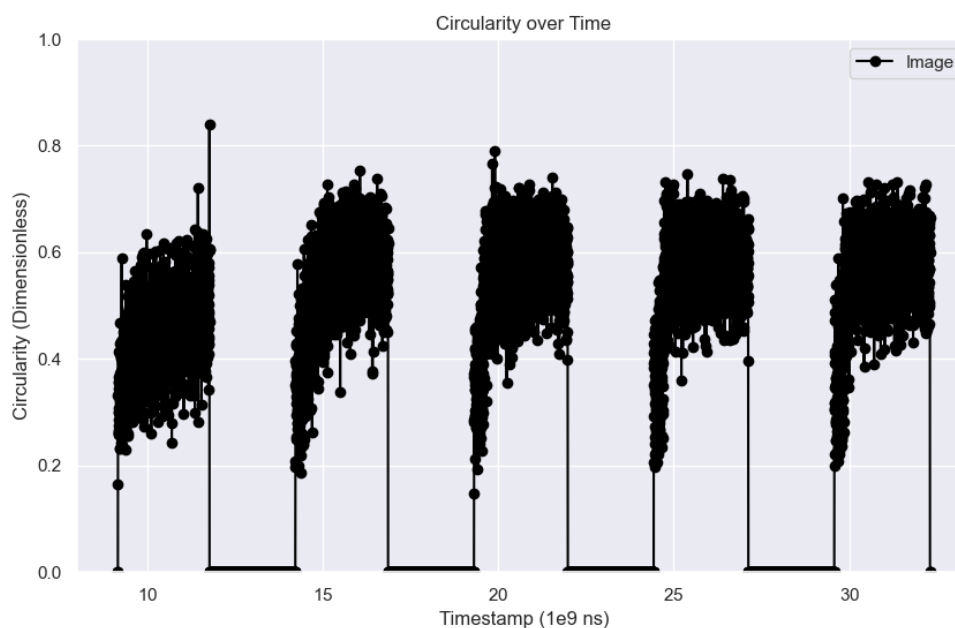


Source: Own (2024) and Fraunhofer ILT (2024)

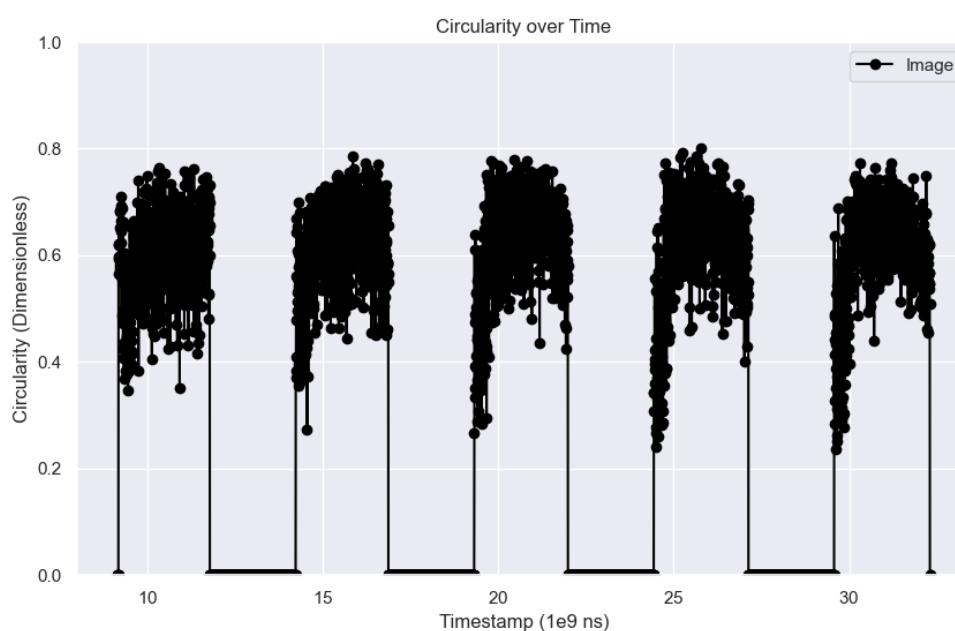
Figure 77 – Brightness Experiment 5 - Camera 220 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

Figure 78 – Circularity Experiment 5 - Camera 520 FPS

Source: Own (2024) and Fraunhofer ILT (2024)

Figure 79 – Circularity Experiment 5 - Camera 220 FPS

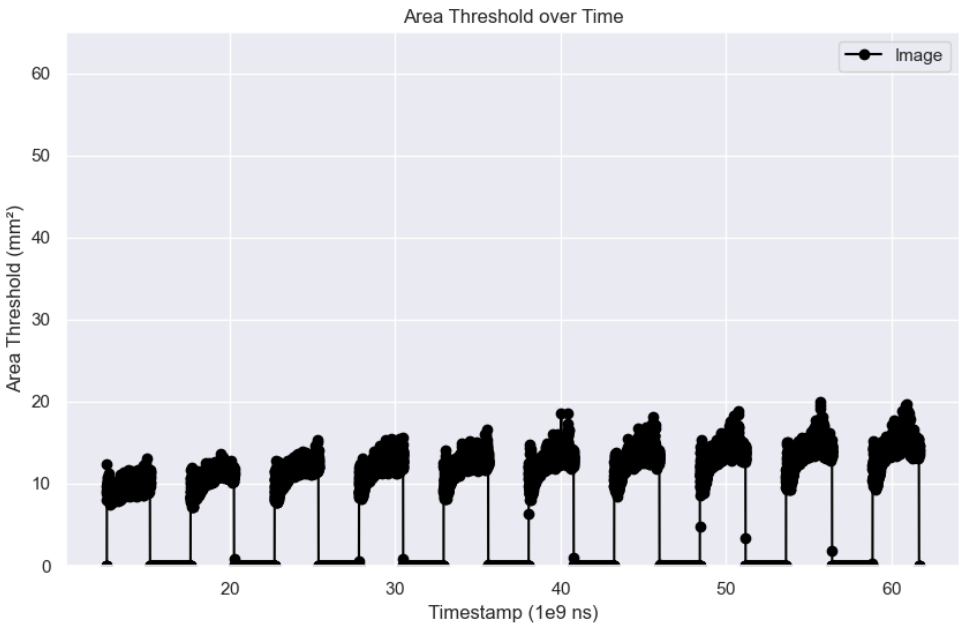
Source: Own (2024) and Fraunhofer ILT (2024)

Experiment 6

Initially, the area thresholds for the camera operating at 520 FPS and 220 FPS are presented in Figures 80 and 81, respectively. Subsequently, the brightness

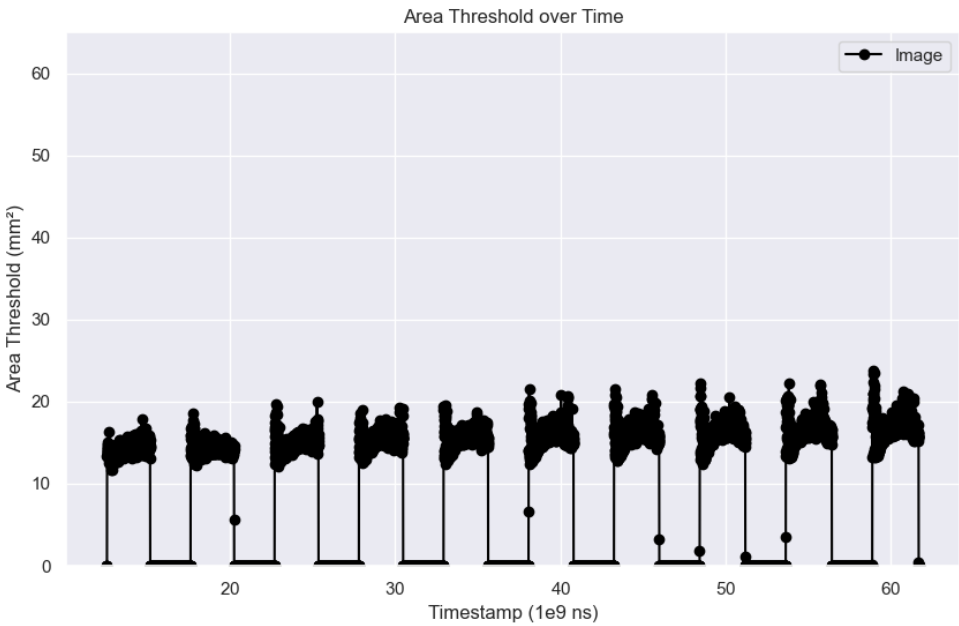
distribution is depicted in Figures 82 and 83, following the same order. Additionally, circularity data is illustrated in Figures 84 and 85.

Figure 80 – Area threshold Experiment 6 - Camera 520 FPS



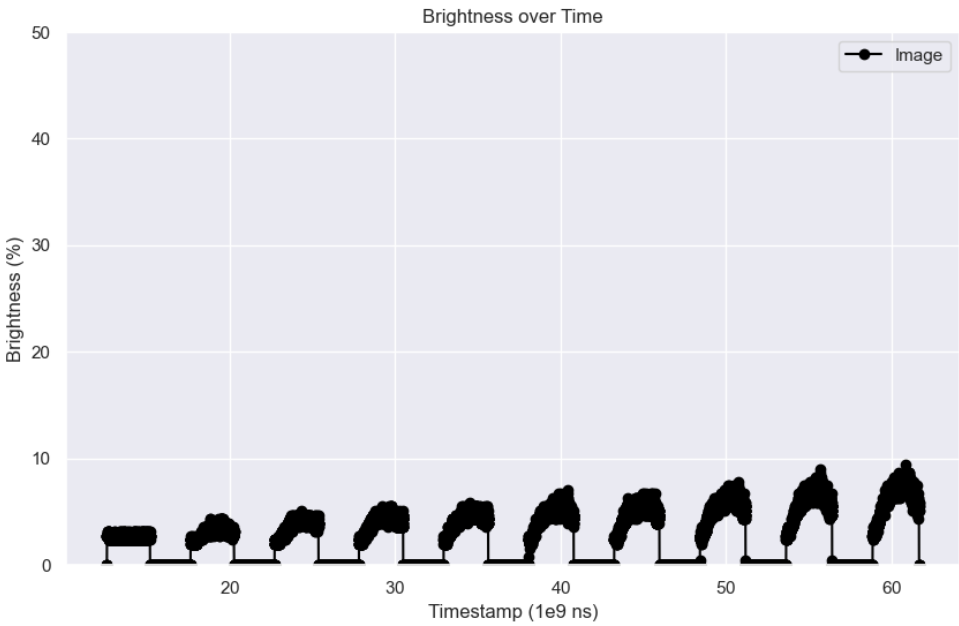
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 81 – Area threshold Experiment 6 - Camera 220 FPS



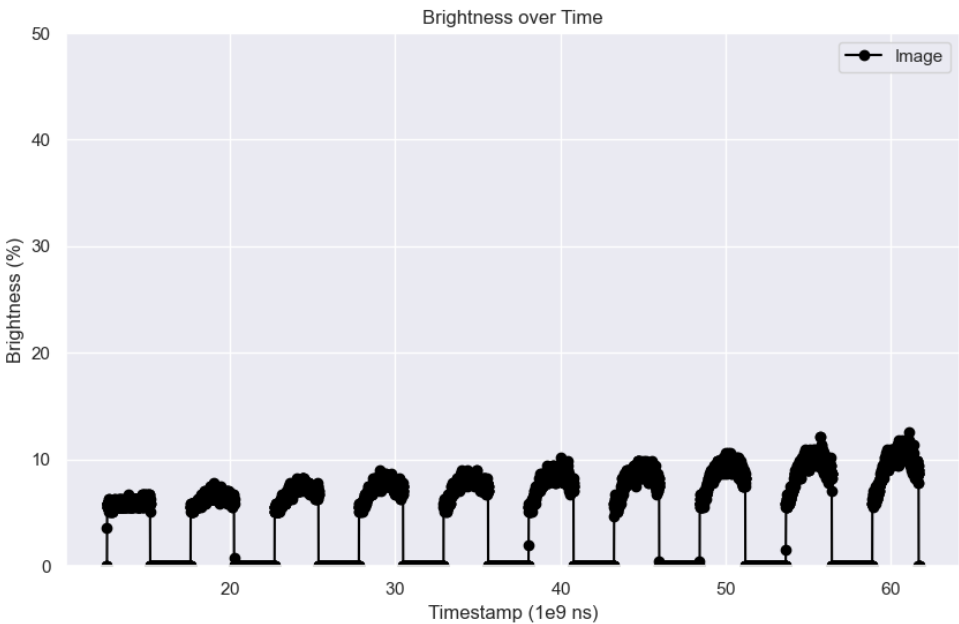
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 82 – Brightness Experiment 6 - Camera 520 FPS



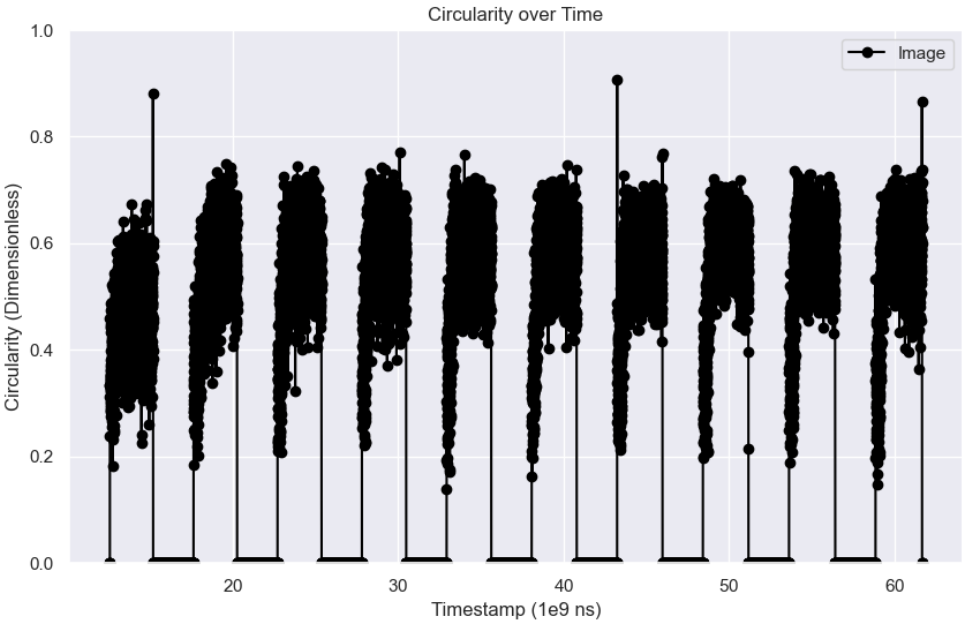
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 83 – Brightness Experiment 6 - Camera 220 FPS



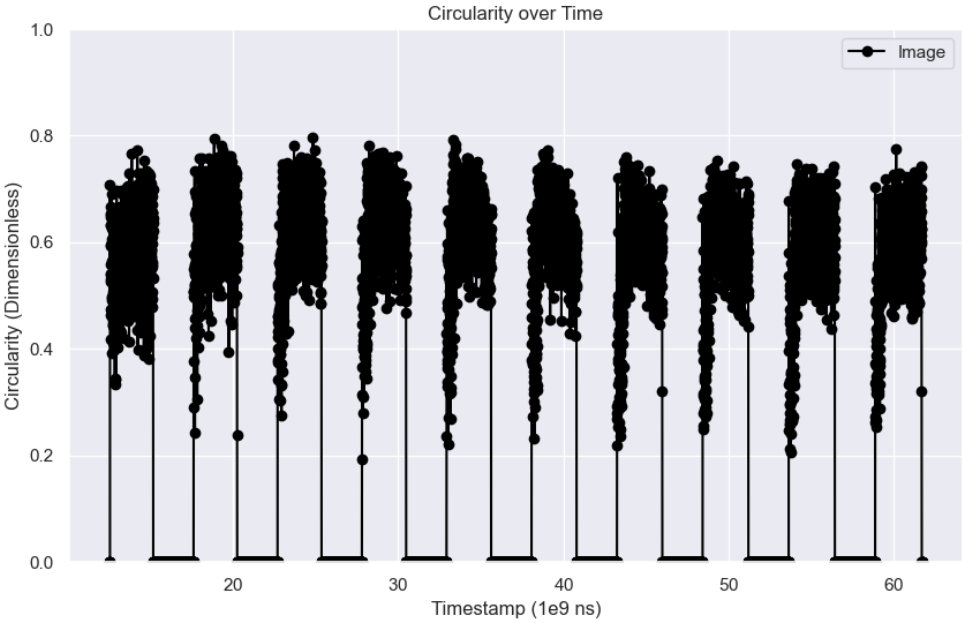
Source: Own (2024) and Fraunhofer ILT (2024)

Figure 84 – Circularity Experiment 6 - Camera 520 FPS



Source: Own (2024) and Fraunhofer ILT (2024)

Figure 85 – Circularity Experiment 6 - Camera 220 FPS



Source: Own (2024) and Fraunhofer ILT (2024)