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Reviewed Paper

INFLUENCING RESIDUAL STRESS IN PBF-LB/M PROCESSES THROUGH IN-PROCESS MICROSTRUCTURE ASSESSMENT AND SELECTIVE LASER HEAT TREATMENT

J. Groenewold[1,*], J. Hammes[1], F. Stamer[1] and G. Lanza[1]

[1] wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
*Corresponding jork.groenewold@kit.edu

Abstract. In powder bed fusion by laser beam melting of metal (PBF-LB/M), residual stresses form in the fabricated layers and affect the process by promoting deformations and cracks. Certain tool steels are especially prone to such defects. This paper presents a concept to reduce residual stresses in the PBF-LB/M manufacturing process of H13 tool steel through selective laser heat treatment, inducing solid-state phase transformations. These directly influence residual stresses due to the associated volume change of the crystal lattice. To assess the microstructure, an eddy current sensor is attached to the coating unit. Local temperature conditions are recorded using a high-speed thermographic camera. The captured data is translated into models using Bayesian optimization and gaussian process regression. Initial results show the successful detection of microstructural changes through in-process laser heat treatments. Subsequently, these measurements and models are utilized determine process parameters for local laser heat treatment. The targeted outcome is a technology that reduces residual stresses, thereby minimizing deformations and cracks in additively manufactured components.

1 Introduction

In the process of powder bed fusion of metal using a laser beam (PBF-LB/M), residual stresses develop in the manufactured material layers due to localized melting and solidification processes and the associated plastic deformations resulting from shrinkage or expansion. These residual stresses negatively impact the manufacturing process as they promote the formation of deformations and cracks. This formation of residual stresses cannot be completely avoided. To enable the additive manufacturing process for challenging materials such as H13 tool steels, the formation of residual stresses must be deliberately controlled.

The formation of residual stresses can be attributed to various factors, including thermal and microstructural reasons [Fitzpatrick, 2003]. Thermal effects typically cause tensile residual stresses, while solid-state phase transformations can induce compressive residual stresses, as studied by Chen et al. (2021) and Narvan et al. (2021). This work is based on the hypothesis that these two opposing effects offer potential to introduce compressive and tensile residual stresses during the manufacturing process.

In the following sections, we will present the state of the art with different approaches to mitigating residual stress, then outline the approach of this work. After that, we will discuss the first results, including eddy current measurements and laser heat treatments to modify the microstructure. Finally, a summary and outlook will be provided.

2 State of the art

Existing approaches to managing residual stresses can be divided into three groups: pre-process, in-process, and post-process. Pre-process approaches focus on simulation-based techniques where the CAD model is "pre-deformed" according to a simulation of the residual stresses [Afazov et al., 2021; Biegler et al., 2020; and Yaghi et al., 2019]. This strategy ensures that the parts meet geometric requirements despite subsequent deformations due to residual stresses. However, these methods are highly complex, requiring detailed simulations of manufacturing and heat treatment post-processing which is computationally expensive. Additionally, they do not eliminate residual stresses, hence they do not prevent the formation of cracks.

In the in-process category, several approaches are pursued. The use of high-temperature build chamber heating involves heating the build chamber to high temperatures to reduce temperature gradients, thereby effectively decreasing residual stresses [Kaess et al., 2023; Marques et al., 2020]. However, this approach requires specialized equipment and adapted machine designs. Without jacket heating for the build cylinder, this method is only effective for the lowest layers and is currently feasible only for small build plates. Additionally, optimizing parameters such as laser power, scanning speed and layer height can also help minimize residual stresses [Shi et al., 2019; Kaya et al., 2021; Kaess et al., 2023]. Despite these optimizations, residual stresses cannot be completely eliminated. Another approach named *EOS Exposure OT & Smart Fusion* involves reducing temperature gradients through thermographic measurements and adjusting laser power via process control parameters, as demonstrated by EOS GmbH [Yağmur et al., 2023]. While this method helps homogenize residual stresses, it does not fully eliminate them.

In the post-process category, various methods are employed after the manufacturing process itself. One common technique is heat treatment, where diffusion processes and recrystallization during stress relief annealing are used to reduce residual stresses [Song et al., 2014; Vrancken et al., 2012]. However, heat treatment does not prevent the formation of cracks and deformations, and it can sometimes cause further deformation. Additionally, the process is very time-consuming. Another technique is laser shock peening, where a high-energy laser pulse vaporizes a thin layer, generating a shock wave that plastically deforms the material, thereby inducing compressive residual stresses [Morgano et al., 2020; Hackel et al., 2018]. However, laser shock peening is also time-consuming and requires specialized equipment.

The existing approaches to managing residual stresses have three main deficiencies: (1) deformations and cracks can only be limitedly avoided, (2) pre- and post-process approaches are very labor-intensive, and in-process approaches often require specialized equipment, and (3) the effect of solid-state phase transformation, as it occurs in certain tool steels, is hardly considered. Therefore, the current strategies for dealing with residual stresses are inadequate for challenging materials when processed with existing industrial equipment. To improve the manufacturing process, the formation of residual stresses must be deliberately controlled.

3 Objective and approach

This approach aims to reduce residual stresses in the PBF-LB/M process using laser heat treatment. This involves inducing a solid-state phase transformation, which, due to the associated volume change of the crystal lattice, directly affects the residual stresses. As shown in Figure 1, after manufacturing each layer, compressive residual stresses can accumulate, leading to deformations and cracks over several layers. The proposed strategy involves locally applying laser heat treatment to modify the microstructure via solid-state phase transformation, thus altering the residual stress locally and resulting in a macroscopically stress-free layer. The checkerboard pattern shown in Figure 1 serves as an illustration, but the precise pattern still needs to be determined.

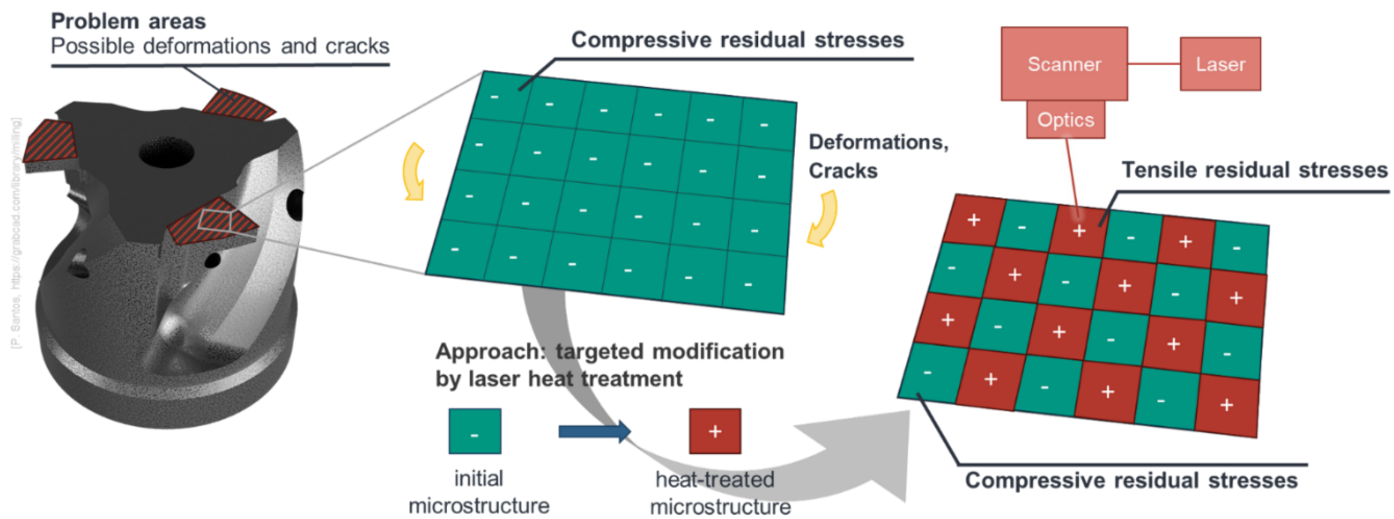


Figure 1: Laser heat treatment approach for local microstructure modification in the PBF-LB/M process.

To effectively influence residual stress in additively manufactured parts, it is essential to understand the current microstructure state after manufacturing each layer and determine the appropriate process parameters for laser heat treatment. The relationship between the process parameters of laser heat treatment and the resulting residual stress can be described through a series of interconnected steps: the chosen laser heat treatment parameters influence the temperature profile, which in turn affects the microstructure, ultimately determining the residual stress. The primary challenges in this endeavor include finding the correct parameters to generate a specific microstructure that corresponds with the desired residual stress state and managing the complexity of the process and material behavior.

To address these challenges and capture the necessary relationships, we integrate measurement technologies into the PBF-LB machine. For monitoring surface temperature, high-speed thermography is employed. This technique, however, is only used during the model development phase and is not intended for use in the later stages of the manufacturing process. For real-time monitoring of the microstructure during the process, eddy current measurement is a suitable technique, as it is sensitive to microstructural changes in metal surfaces [Sahebalam et al., 2014]. Unlike other methods such as X-ray diffraction (XRD), which are not feasible for in-process measurement integration, eddy current systems can be integrated into the PBF-LB machine.

These integrated measurement techniques enable the development of models that describe the relationships between laser heat treatment parameters, temperature profiles and microstructural changes. By leveraging these models, we aim to manipulate material phases and, consequently, control residual stresses in the manufactured parts.

As a material, AISI H13 (1.2344) will be used due to its significant solid-state phase transformations. Research by Chen et al. (2021) and Narvan et al. (2021) has demonstrated that these transformations are strongly influenced by the temperature history during the PBF-LB process, leading to the formation of different microstructures. Additionally, this material is extensively used in high-performance applications, providing a substantial amount of comparative data for its material properties.

The implementation plan for this approach is divided into three sections: (1) integration of eddy current sensor and data processing to determine microstructure during manufacturing, (2) development of process and material models using Bayesian optimization to determine process parameters for needed laser heat treatment and (3) performing laser heat treatments inside PBF-LB machine. An overview of the targeted technical implementation is shown in Figure 2, and is described in detail in the following sections.

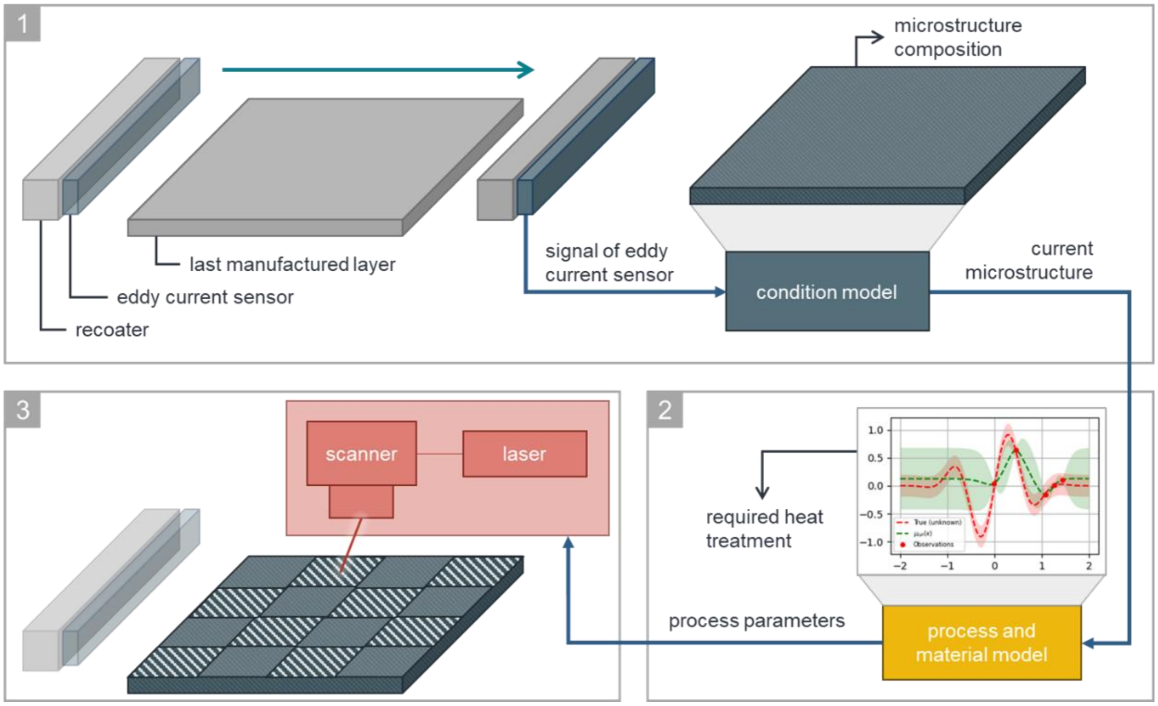


Figure 2: Technical implementation of in-process measurement and laser heat treatment, involving: (1) an eddy current sensor on the recoating unit collects data during recoating without new powder and a condition model determines microstructure composition from the data, (2) a process and material model derives necessary heat treatment parameters, and (3) laser heat treatment locally modifies the microstructure.

3.1 Eddy current sensor and microstructure measurement

The eddy current measurement technique utilizes electromagnetic induction to assess material properties non-destructively. This method involves inducing currents in a conductor, which generate localized magnetic fields that interact with the material's surface. By analyzing changes in these fields, precise measurements of conductivity can be carried out. The eddy current measurement technique is sensitive to changes in microstructure as these influence the electromagnetic properties [Sahebalam et al., 2014].

One of the primary challenges in utilizing eddy current sensors within the PBF-LB/M process is that the sensor's signal is not solely influenced by the material phase but also by defects such as pores and surface roughness. These additional factors complicate the accurate differentiation of material phases, necessitating a comprehensive approach to model development. To address this challenge, a full factorial design for the fabrication of test specimens is employed. The material chosen for this study is AISI H13, which is subjected to various process and post-process conditions to create a range of microstructures as well as defect and surface states. The factorial design includes the following factors: (1) the microstructure, which will be influenced through a controlled heat treatment process, and the covariates of (2) relative density and (3) surface condition, which will be manipulated via the PBF-LB process and post-process surface treatment, respectively.

Following the fabrication of these test specimens, data acquisition is carried out. The data collected from these samples is then used to develop models for the eddy current sensor. The input data for these models consists of complex numbers, which undergo a process of feature extraction. The output data is the microstructure of the test specimen surface in terms of retained austenite. Subsequently, regression models are employed to establish relationships between the extracted features and the presence of retained austenite. These models should enable precise differentiation between the material phases and be robust against the influence of relative density and surface properties.

The final step is to integrate this measuring system into an existing PBF-LB/M machine. For this purpose, the measuring system is mounted on the coater of the machine, as shown in Figure 2, so that the near-surface microstructure can be characterized by moving the coater after the production of each layer before and after the heat treatment process.

3.2 Process and material model

Having integrated an eddy current measurement system to assess the microstructure during manufacturing, the next step is to actively influence microstructural properties using laser-heat treatment. This requires the development of process and material models.

The challenge in laser heat treatment processes lies in the multitude of input variables, such as power, scan speed, and focus distance, combined with the inherent complexity of material behaviors. These factors significantly influence the temperature distribution and the resulting microstructure. The physical modeling of the temperature distribution and phase transformations involved is highly intricate and computationally intensive. Consequently, an empirical substitute model is being developed to address these challenges.

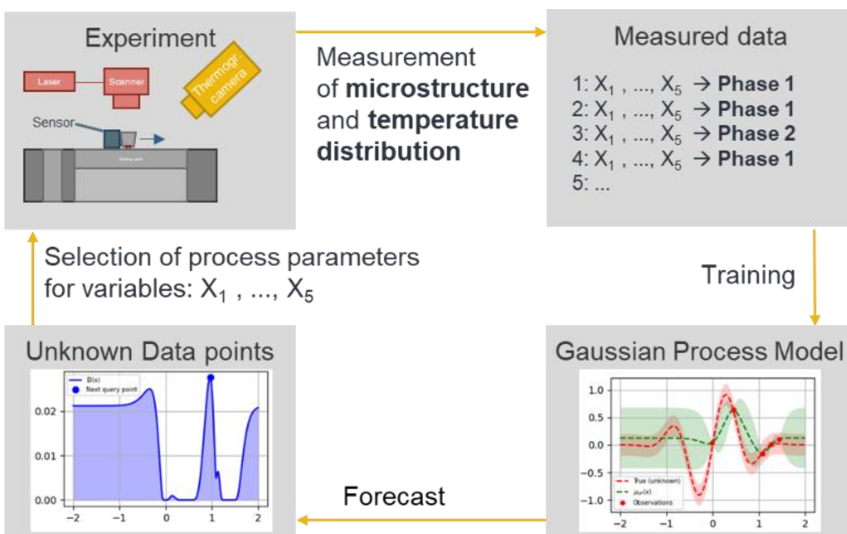


Figure 3: Approach to learning the process and material model using Bayesian optimization and gaussian process models.

For the development of empirical models, the temperature distribution and microstructure are assessed using in-process measurement techniques. To measure the temperature distribution accurately, high-speed thermography is utilized during the development phase. The resulting microstructure is assessed using the eddy current sensor, as described in the initial section of this approach. Given the extensive number of input variables, traditional Design of Experiments (DoE) methodologies become impractical due to the sheer volume of necessary experiments. Therefore, Bayesian optimization is employed to efficiently navigate the experimental design space (see Figure 3). The overall methodology can be summarized as follows:

1. Experiment: An experiment (index i) is carried out with a set of process parameters $\mathbf{X}_i$, including laser power ($X_{i,1}$), scan speed ($X_{i,2}$), focus distance ($X_{i,3}$), hatch distance ($X_{i,4}$), and hatch strategy ($X_{i,5}$).
2. Measurement: During the experiment, both the resulting microstructure $Y_i = f(\mathbf{X}_i)$ and temperature distribution $Z_i = f(\mathbf{X}_i)$ are measured for this specific set of process parameters $\mathbf{X}_i$. The temperature distribution Z_i here serves as an auxiliary variable.

3. Training the Gaussian Process Model: The collected data is then used to train a Gaussian process model. Gaussian process models are advantageous as they account for uncertainty in the predictions they make, providing a probabilistic framework that is essential for our optimization efforts [Shahriari et al., 2016].
4. Creating an acquisition function to select parameters $\mathbf{X}_{i+1}$ for next experiment: The model's uncertainty is exploited to develop an acquisition function. This function helps determine the next set of process parameters for subsequent experiments. The acquisition function is a key component in Bayesian optimization, guiding the search for optimal conditions [Shahriari et al., 2016].

This process forms an iterative loop, where each cycle involves conducting an experiment, updating the model with new data, and using the acquisition function to select new parameters. Through this iterative approach, the underlying relationships between process parameters and outcomes are gradually captured and refined within the model. By employing this Bayesian optimization approach, we aim to drastically reduce the number of experiments need and be able to precisely identify the necessary process parameters for laser heat treatment to achieve a desired microstructure. In our study, considering that we have $d = 5$ input variables, we estimate that approximately 50 runs will be necessary for an initial Bayesian optimization experiment. This estimation follows the empirical guideline by Loeppky et al. (2009) that suggests $n = 10\ d$ runs to achieve a reasonable level of prediction accuracy.

3.3 Laser heat treatment

This last part of the approach, the laser heat treatment, integrates the results from sections 3.1 and 3.2 and allows for control over microstructural characteristics. This technique faces several challenges, particularly the feasibility of its application within a PBF-LB machine. The primary concern is the process parameter window available, as the laser is typically used for melting material rather than mere heat treatment, and maintaining productivity at the same time. Additionally, the method's effectiveness in achieving precise local microstructural adjustments is crucial.

To address these challenges, samples need to be produced and locally adjusted. These samples will be characterized in terms of the possible minimal size of the modified pattern, the transition between different microstructural regions, and the depth of laser heat treatment. So far, the primary focus has been on altering the microstructure. Moving forward, it is necessary to validate this approach and quantify the reduction in residual stresses. This will demonstrate its capability to reduce warping and cracking, thus confirming the technique's overall efficacy.

4 Results

The two most crucial prerequisites for the presented approach are the accurate measurement of different microstructures using the eddy current sensor and the feasibility of in-process laser heat treatment to influence microstructure. Consequently, the initial steps involve the integration of the sensor and conducting experiments with laser heat treatment. The outcomes of these steps are detailed below.

4.1 Eddy current sensor

The integration of the eddy current sensor is shown in Figure 4 (a). Here, the measurement system W1 from the company AMiquam SA is used. The system consists of a wireless acquisition module continuously collecting data from the sensors, which are attached to the recoating mechanism system, enabling the system to monitor the process between recoating steps. This setup includes two probes, each of which covers a line when moving over the build plate area.

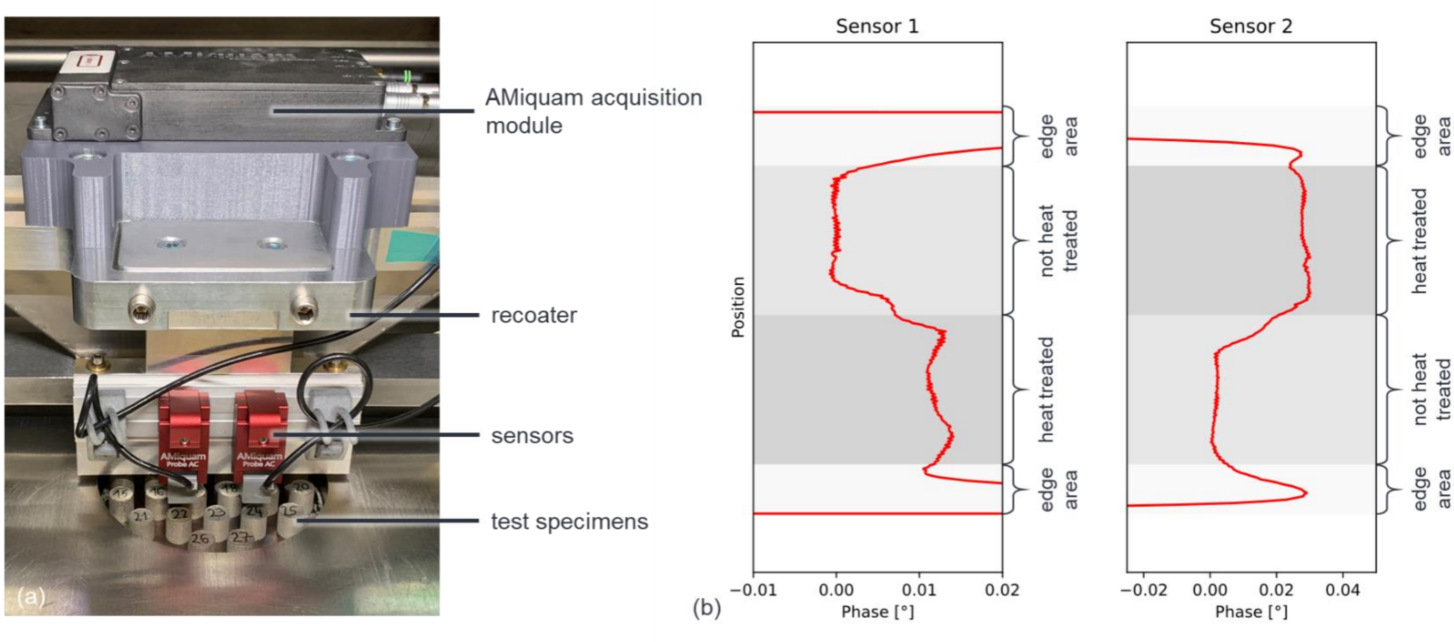
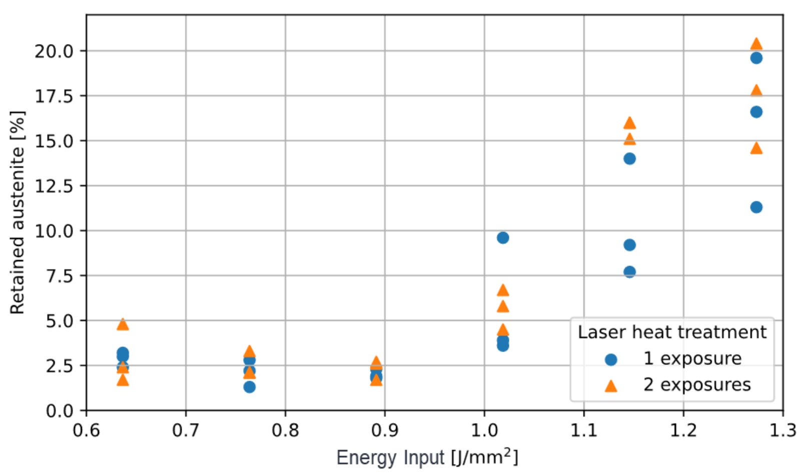


Figure 4: Eddy current measurement in SLM280 HL machine. (a) Integration of AMiquam measurement system and (b) first measurement using H13 test specimens.

Figure 4 (b) illustrates the first measurements conducted using two H13 bulk material test specimens. For each test specimen, the half of the surface has laser heat treated. The graphs present the signal phase data from each sensor probe as they moved over the specimens. The results show an increased signal phase in the heat-treated areas. The prominent signal change in the marked edge area is attributed to edge effects caused by uneven eddy current distribution. Overall, these results demonstrate the sensor's capability to accurately detect the change in microstructure.

4.2 Laser heat treatment in SLM 280 HL machine

The goal in regard to the laser heat treatment is to develop a strategy that enables laser heat treatment within the used SLM 280 HL machine using the integrated 400W fiber laser by IPG. The approach involves utilizing the defocus of the laser to achieve the desired microstructural changes. The experiments were conducted using conventional H13 bulk material, which was turned and ground into specimens with dimensions of Ø30 mm and a height of 10 mm. The process parameters are indicated in Figure 5.



Laser HT parameters	
Power:	50 – 100 W
Scan speed:	200 mm/s
Spot diameter:	500 µm
Hatch distance:	0.15 mm

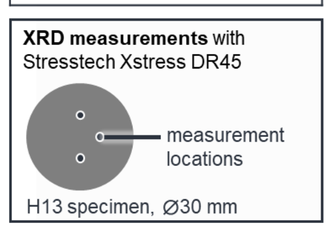


Figure 5: Measurements of retained austenite for laser heat-treated H13 specimens.

Figure 5 presents the relationship between retained austenite and laser power, measured using X-ray diffraction. The results confirm that by adjusting the laser defocus via the build platform position, it is possible to alter the microstructural composition of the material using the standard laser in the SLM 280 HL machine. This demonstrates the feasibility of in-process laser heat treatment to influence microstructure, supporting the overall approach.

5 Summary and outlook

The targeted outcome of this approach is to develop a technology for laser heat treatment in the context of the Powder Bed Fusion by Laser Beam of Metal (PBF-LB/M) process. This technology aims to enable localized solid-state phase transformation based on in-process detection of microstructure composition, ultimately reducing residual stresses in additively manufactured components.

To achieve this, the approach involves qualifying in-process measurement equipment to assess the microstructure composition of additively manufactured layers. Using the data obtained from these measurements, process and material models for laser heat treatment will be developed. These models will be based on Bayesian optimization and Gaussian Process models, which will determine the optimal process parameters for local laser heat treatment aimed at modifying the microstructure in specific regions. The overall goal is to minimize deformations and cracks during the additive manufacturing process, thereby significantly enhancing the quality and reliability of the manufactured components.

The integration of the eddy current sensor and the initial experiments with laser heat treatment have shown promising results. The next steps will focus on refining these methods and further evaluating the sensor signals to build a comprehensive model for assessing microstructure. Based on these findings, detailed process and material models will be developed.

In addition to the presented approach, a critical question that still needs consideration is the penetration depth of the laser heat treatment. Influencing the microstructure in the last manufactured layer alone is insufficient to impact residual stress throughout the part. The laser heat treatment must penetrate deeply enough so that the effects, such as changes in microstructure, are not negated by subsequently manufactured layers. This aspect of the process will require further investigation to ensure effectiveness of the proposed approach in additive manufacturing applications.

6 Acknowledgements

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7 References

Afazov, Shukri; Semerdzhieva, Eleonora; Scrimieri, Daniele; Serjouei, Ahmad; Kairoshev, Bekmurat; Derguti, Fatos (2021): An improved distortion compensation approach for additive manufacturing using optically scanned data. In: Virtual and Physical Prototyping 16 (1), S. 1–13. DOI: 10.1080/17452759.2021.1881702.

Biegler, Max; Elsner, Beatrix A. M.; Graf, Benjamin; Rethmeier, Michael (2020): Geometric distortion-compensation via transient numerical simulation for directed energy deposition additive manufacturing. In: Science and Technology of Welding and Joining 25 (6), S. 468–475. DOI: 10.1080/13621718.2020.1743927.

Chen, Wei; Xu, Lianyong; Han, Yongdian; Zhao, Lei; Jing, Hongyang (2021): Control of residual stress in metal additive manufacturing by low-temperature solid-state phase transformation: An experimental and numerical study. In: Additive Manufacturing 42, S. 102016. DOI: 10.1016/j.addma.2021.102016.

Diegel, Olaf; Nordin, Axel; Motte, Damien (2019): A Practical Guide to Design for Additive Manufacturing. Singapore: Springer (Springer eBooks Engineering).

Hackel, Lloyd; Rankin, Jon R.; Rubenchik, Alexander; King, Wayne E.; Matthews, Manyalibo (2018): Laser peening: A tool for additive manufacturing post-processing. In: Additive Manufacturing 24, S. 67–75. DOI: 10.1016/j.addma.2018.09.013.

Kaess, Moritz; Werz, Martin; Weihe, Stefan (2023): Residual Stress Formation Mechanisms in Laser Powder Bed Fusion-A Numerical Evaluation. In: Materials (Basel, Switzerland) 16 (6). DOI: 10.3390/ma16062321.

Kaya, Mert; Sunay, Nedim; Kaynak, Yusuf (2021): Comparison of finite element and empirical model prediction of surface residual stress in inconel 718 parts fabricated by laser powder bed fusion additive manufacturing. 592 Pages / Journal of Additive Manufacturing Technologies, Vol. 1 No. 3 (2021): J AM Tech. DOI: 10.18416/JAMTECH.2111592.

Loeppky, J. L., Sacks, J. & Welch, W. J. (2009). Choosing the Sample Size of a Computer Experiment: A Practical Guide. Technometrics, 51(4), 366–376. https://doi.org/10.1198/tech.2009.08040

Marques, Bruno M.; Andrade, Carlos M.; Neto, Diogo M.; Oliveira, Marta C.; Alves, José L.; Menezes, Luís F. (2020): Numerical Analysis of Residual Stresses in Parts Produced by Selective Laser Melting Process. In: Procedia Manufacturing 47, S. 1170–1177. DOI: 10.1016/j.promfg.2020.04.167.

Morgano, M.; Kalentics, N.; Carminati, C.; Capek, J.; Makowska, M.; Woracek, R. et al. (2020): Investigation of the effect of Laser Shock Peening in Additively Manufactured samples through Bragg Edge Neutron Imaging. In: Additive Manufacturing 34, S. 101201. DOI: 10.1016/j.addma.2020.101201.

Narvan, Morteza; Ghasemi, Ali; Fereiduni, Eskandar; Kendrish, Stephen; Elbestawi, Mohamed (2021): Part deflection and residual stresses in laser powder bed fusion of H13 tool steel. In: Materials & Design 204, S. 109659. DOI: 10.1016/j.matdes.2021.109659.

Sahebalam, A., Kashefi, M. & Kahrobaee, S. (2014). Comparative study of eddy current and Barkhausen noise methods in microstructural assessment of heat treated steel parts. Nondestructive Testing And Evaluation, 29(3), 208–218. https://doi.org/10.1080/10589759.2014.914207

Shahriari, B., Swersky, K., Wang, Z., Adams, R. P., & De Freitas, N. (2016). Taking the human out of the Loop: A review of Bayesian Optimization. Proceedings of the IEEE, 104(1), 148–175. https://doi.org/10.1109/jproc.2015.2494218

Shi, Wentian; Wang, Peng; Liu, Yude; Han, Guoliang (2019): Experiment of Process Strategy of Selective Laser Melting Forming Metal Nonhorizontal Overhanging Structure. In: Metals 9 (4), S. 385. DOI: 10.3390/met9040385.

Song, Bo; Dong, Shujuan; Liu, Qi; Liao, Hanlin; Coddet, Christian (2014): Vacuum heat treatment of iron parts produced by selective laser melting: Microstructure, residual stress and tensile behavior. In: Materials & Design (1980-2015) 54, S. 727–733. DOI: 10.1016/j.matdes.2013.08.085.

Vrancken, Bey; Thijs, Lore; Kruth, Jean-Pierre; van Humbeeck, Jan (2012): Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties. In: Journal of Alloys and Compounds 541, S. 177–185. DOI: 10.1016/j.jallcom.2012.07.022.

Yaghi, Anas; Ayvar-Soberanis, Sabino; Moturu, Shanmukha; Bilkhu, Ravi; Afazov, Shukri (2019): Design against distortion for additive manufacturing. In: Additive Manufacturing 27, S. 224–235. DOI: 10.1016/j.addma.2019.03.010.

Yağmur, A., Pääkkönen, I. & Miles, A. (2023). The Hitchhiker's Guide to Smart Fusion. https://3d.eos.info/white-paper-smart-fusion.