Lasers in Manufacturing Conference 2023

Influences of optical errors in the SLM process with high separation angle beam splitting

Florian Joachim Oskar Spieth[a,*], Thorsten Heeling[a], Hans-Christian Moehring[b]

[a]Robert Bosch Manufacturing Solutions GmbH, Wernerstraße 51, 70469 Stuttgart, Germany
[b]Institute for Machine Tools University Stuttgart, Holzgartenstraße 17, 70174 Stuttgart, Germany

Abstract

Higher productivity, especially higher build rates are necessary for a widespread use of additive manufacturing in series production. In selective laser melting (SLM) these improvements are currently focusing on strategies for beam shaping and splitting to increase the power input in the melt pool. Nevertheless, the power to be absorbed in the melt pool is limited by its size which leads to the trade-off between accuracy and build rate. To avoid this limit, the use of a beam splitter with resulting spot distances of over 25 mm is investigated. This could be used to build up three parts in parallel. While this offers great potential for productivity increases, optical errors like distance, focus and rotation errors are inherent to the setup and need to be understood for future compensation strategies. The influences of these errors are analyzed and discussed for stainless steel 316L specimens.

Keywords: beam splitting; selective laser melting; stainless steel 316L

1. Motivation

Current commonly used approaches to increase the productivity of SLM aim for an increase in melt pool size or multiple laser systems. These approaches either decrease the resolution of the process or increase the necessary investment cost substantially. This leads to a disadvantage for the SLM process compared to conventional production processes for high volume serial production. To mitigate this disadvantage beam splitters could be used to parallelize the production of parts with multiple laser spots for multiple parts, while keeping the investment costs lower through using only one optic system. This approach is currently used for

* Corresponding author. Tel.: +49-711-811-21319
E-mail address: florian.spieth@de.bosch.com

applications in the fields of laser drilling and shows great potential there. Yet a simple transfer of the systems used in laser drilling is not feasible because of the different ratios of needed spot distance to focus diameter. For SLM a wider separation angle of the beam splitter is necessary to build up multiple parts in parallel. But the optical errors inherent to the use of beam splitters increase with increasing separation angle of the beam splitter and thereby resulting in stronger influences on the process results. To understand these influences better multiple test specimens were built and investigated regarding geometrical inaccuracies and resulting densities.

2. State of the art

The need for higher productivity, especially higher build rates is supported by current research in the field. The current bottleneck is the power that can be absorbed by a melt pool of certain size without resulting in severe overheating, evaporation and spattering. To solve the limitations regarding power per melt pool currently either the number of melt pools is increased e.g., by an increase of laser scanner systems above the same field of view (Molotnikov et al. 2021) or the size of the melt pool is increased by larger powder layer heights (Sinico et al. 2022) or altered laser beams e.g.: beam shaping (Galbusera et al. 2023) and beam splitting (Slodczyk et al. 2021). If an increase in melt pool size is not viable the field of beam splitting promises an increase in build rate by an increase in the number of beams.

Current research for laser manufacturing with beam splitting can be categorized in parallel laser drilling, multi-beam SLM and multi-melt pool SLM. First, the idea of using beam splitters to increase laser processes in manufacturing is nothing new as Büsing, describes it for the scanner-based material processing with ultra-short laser pulses. In his work a method for the design of an optimal optical setup is described. But these optimizations always contain a remaining inherent optical error. (Büsing et al. 2014) In the work of Hofmann et al. a method for the compensation of these optical errors with multiple glass cubes mounted to galvo scanners is presented (Hofmann et al. 2020).

For an application in SLM certain boundary conditions change e.g., larger spot diameters, continues wave lasers and higher necessary average laser power inputs. The benefits of such are presented in the work of Heeling by the synchronized use of a pair of laser scanner systems and consist of improved wetting behavior and a reduction of the cooling gradient which leads to less cracks und pores in the solidified material (Heeling 2018). Additional in the work of Slodczyk et al. the amount of spatter with higher laser powers in one melt pool could be reduced significantly using a beam splitter. That way multiple singular laser beams enter one melt pool separately. (Slodczyk et al. 2021) Further improvements are promised by the separation of the melt pool for multiple beams in multiple smaller melt pools. One of the approaches in this field is the one of Tsai et al. where the laser beam is separated by a beam splitter and a tele-centric lens. This approach reduces the optical errors significantly because the beam distance is not increasing after the tele-centric lens. Using this approach an alternating scanning strategy with a spot distance of less than 1 mm showed a multiplication for the achievable build rate. (Tsai et al. 2019) The work of Yu et al. investigates the use of this technology to produce NdFeB magnets. There an increase in maximum magnetic energy product and a decrease in processing time of 38% is achieved (Yu et al. 2022). A different approach is presented in the work of Lantzsch et al. with the use of two laser in one scanner system, where a control of the lateral relative position of the two laser spots is possible. Using this system, an increase of productivity of circa 90% is reported. (Lantzsch et al. 2021) While current literature shows great potential for increases in productivity with beam splitting for SLM, the influence of high separation angles in beam splitting is to be further investigated.

3. Methods

The experiments are conducted on a laboratory SLM machine with 316L stainless steel. A near infra-red continues wave laser with a wavelength of 1070 nm is used as laser source. The parameters are set to a laser power of 680 watts, a scan speed of 1000 mm/s and a hatch distance of 100 µm. As test specimen a cube with an edge length of 10 mm and a hatch rotation of 90 degrees are built. The density analysis is conducted with metallographic and archimedes principle based methods The power deviation in between the different laser beams is measured with a power meter. The different cubes are in different positions on the build plate, as shown in Fig 1 to analyze the influence of the position dependent optical errors.

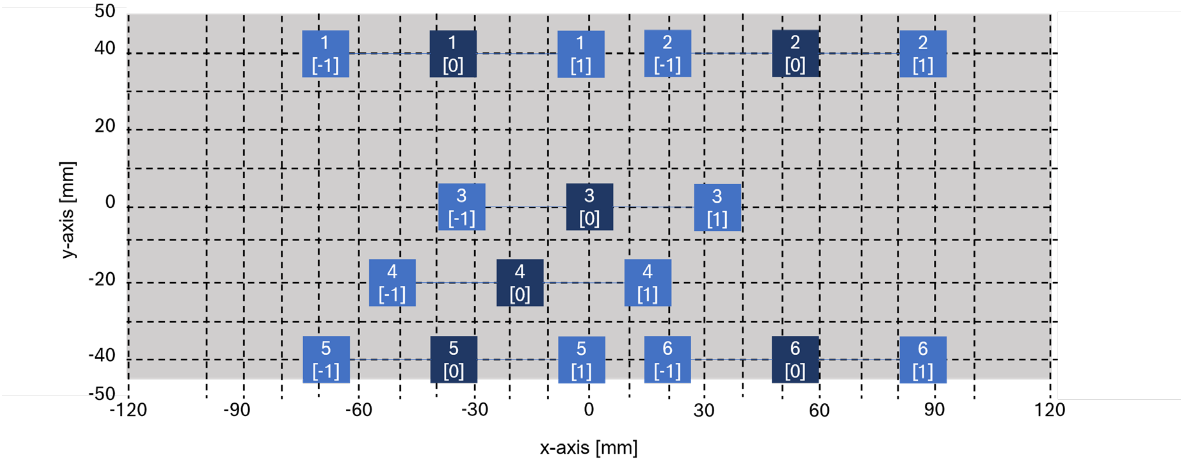

Fig. 1. Cube positions on the build plate relative to the build plate center in consecutive numbers and with respective order numbers

Further a 3x1 one-dimensional beam splitter is placed in between the focusing unit and the scanner system. There, the beam is split in three beams propagating with a separation angle to the direction of the center beam. This separation angle leads to a spot distance in between the three resulting laser spots on the build plate of larger than 25 mm. An overview of the optical system is given in Fig 2. There the beams are defined by their order number increasing from the center outwards with 0 for the center beam and -1 as well as 1 for the side beams in negative and positive x-direction of the scanner coordinate system.

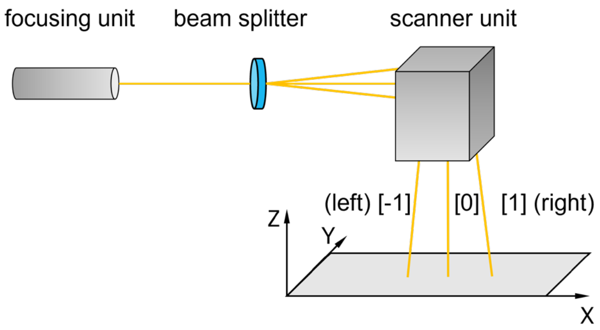

Fig. 2.: overview of the optical system

The non-parallel beams result in optical errors for the deflection of the beams on the build plate. Similar to the work of Büsing et al. the three optical errors: spot distance error, rotation error and focus error are chosen for this analysis, as depicted in Fig 3 (Büsing et al. 2014). The spot distance error describes the changes in relative lateral position of the side beams to the center beam on the build plate for different target positions of the center beam. From results of markings with a beam splitter on anodized aluminum plates a maximum spot distance error of 1.2 mm for the specific machine is known. While this leads to a position error of the test cube build by the side beam, the influence on the density of the test specimen is neglectable due to the small gradient of the position error increase leading to variations in the hatch distances of less than 2 µm.

The rotation error describes the difference of the angle in between a straight line through the centers of the side beams at any position and the centers of the side beams in the origin position of the scanner coordinate system. Similar to the effects of the spot distance error the rotation error influences the position of the test specimen yet does not affect the density of the cube due to the small gradient of the change in rotation error over the position on the build plate.

Of the optical errors, mainly the focus error, describing the change in focus diameter due to beam travel length differences of the side beams to the center beam, is expected to have an influence on the density of the cubes. Additional influence on the density is expected from a power error due to not fully homogeneous separation of the laser power with the beam splitter in the three beams. To further understand the individual influence of both errors the laser power is analyzed depending on beam and position on the build plate.

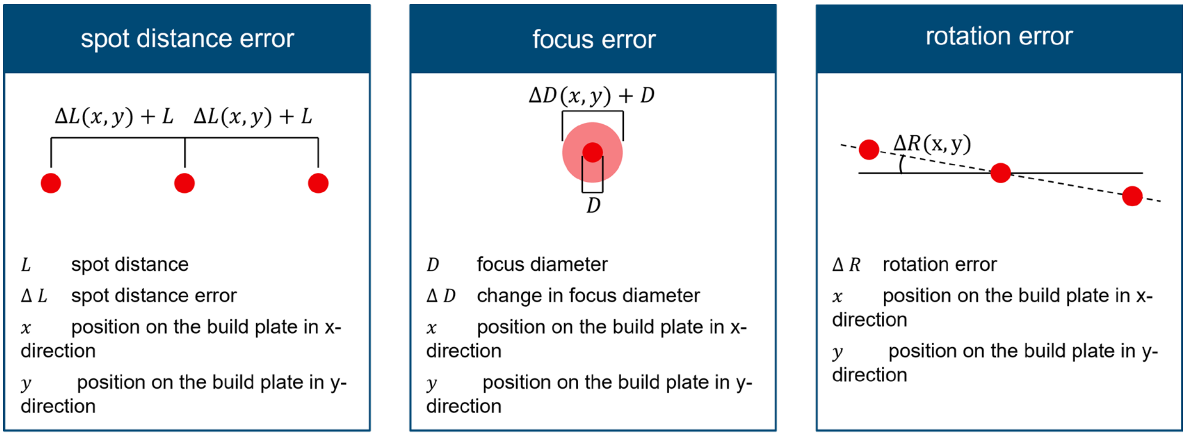

Fig. 3. Overview of the spot distance error, focus error and rotation error

4. Results & Discussion

The measurement of the laser power shows a difference in available laser power per beam. The average power level of the side beams is 87.9% of the center beam independent of the position on the build plate. All measured values at the center and the corners of the build plate differ by a maximum variance of 2.8 % to the average laser beam power. This variance is most likely a result of the power meter's measurement error. With the understanding of these differences in laser power, the expected influence would be homogeneous for all triplets of cubes with equal lower densities for the cubes built by the side beams compared to the ones built by the center beam. Yet the results of the metallographic density analysis, depicted in Fig 4, show lower not homogeneous distributed densities for the side cubes.

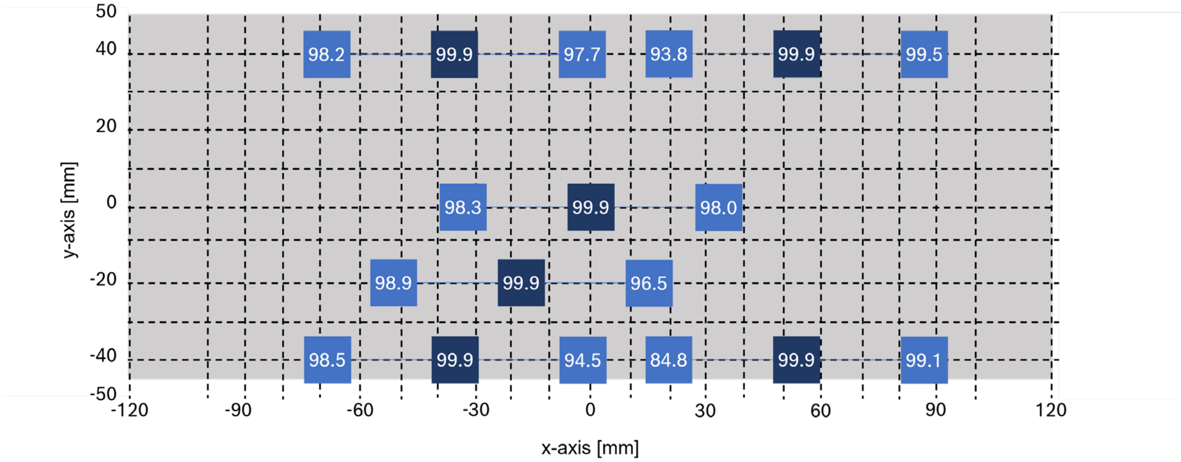

Fig. 4. Metallographic measured densities of the cubes on the build plate

On one hand, the densities of the cubes built with the center beam remain above 99.9% for all positions. This highlights the sufficiency of the process parameters for building dense cubes. Yet on the other hand the cubes built with the side beams vary in density depending on their position and order number of the side beams from 99.5% in the maximum to 84.8% in the minimum. While the influence of the deficit in laser power for the side beams leads to lower densities for all positions on the build plate, the achieved densities are distributed inhomogenously. This strengthens the need to investigate the optical errors aside from pure laser power deviations. For further investigating the metallographic microsections are depicted in Fig. 5. There the porosities are distributed homogeneous in the cubes. Yet a symmetrical density deficit is visible for the cubes built in the center of the build plate, while the cubes in the border area of the build plate show asymmetric densities in between the cubes built by the side beams. Besides that, the results for the whole build plate show increases in densities for different cubes above the density of the side beams in the center.

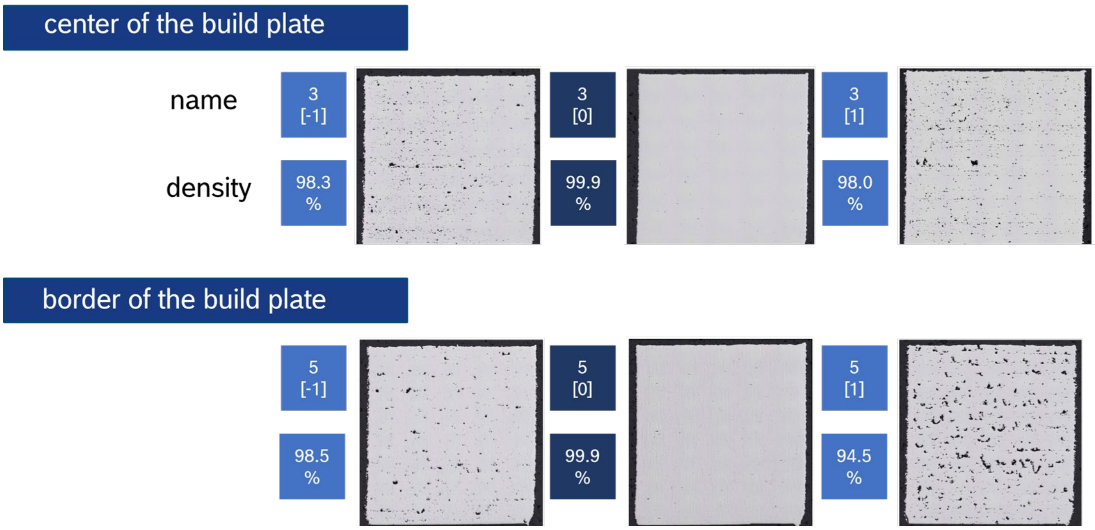

Fig. 5. Examples for metallographical analysis of cubes

Further the density of the side cubes closer to the center of the build plate is lower than their more distanced counterpart, which might be an effect of the focus error increasing with greater length differences to the center beam. Due to these inhomogeneities of the density distribution the consideration of the focus error as a viable cause for these results is reasonable. To check if there is a correlation between the focus error and the densities, the densities depicted in Fig 6, are sorted in regard to their simulated focus error based on the beam travel lengths. While the cubes of the laser with the order number -1 show a strong correlation with the focus error, the ones of the other side beam do not. The difference in the side beams' density distribution is yet unknown and will be focused on upcoming work. The increase in spot diameter due to the larger beam length is expected to result in insufficient fusion as seen in the results of the -1 beam. Because of the larger beam diameter, the input power is distributed over a wider area and therefore resulting in wider, less deep melt pools which increase the chance for lack of fusion defects.

To underline these findings the cubes' densities are additionally measured with the archimedes principle, for which the results show the same effects. Although, the measurements show higher densities than the metallographic analysis. This effect is most likely to result from open pores which allowed the measurement liquid to enter the specimen in the border areas of the cubes, which influences the measurement error to increases with lower densities.

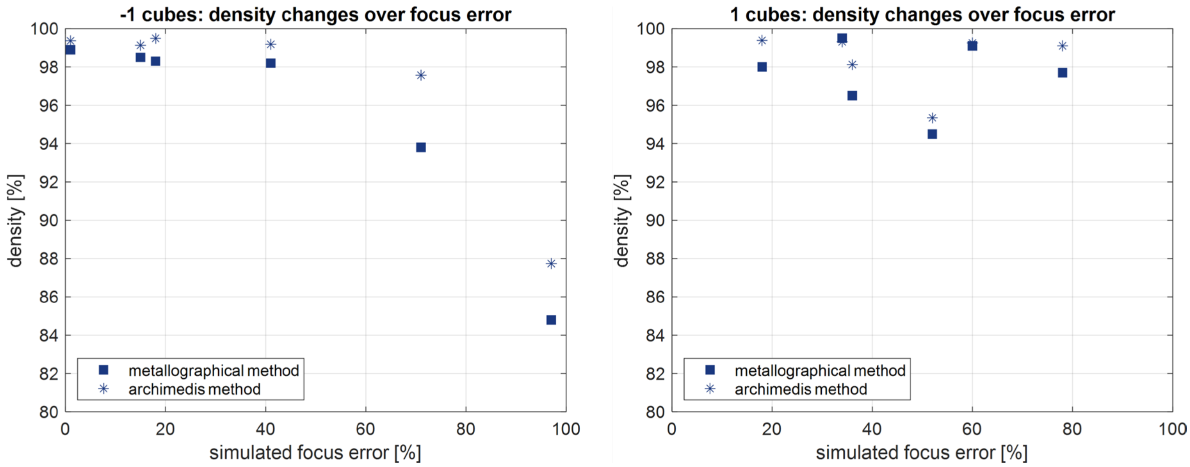

Fig. 6. Overview of the spot distance error, focus error and rotation error

5. Outlook & Summary

The use of a beam splitter in a SLM machine for the simultaneous build is possible but leads to a large decrease in the density of specimens built with the side beams. This challenge is mostly fueled by the differences in laser power and the position dependent focus error. On one side the power differences lead to density deficits for the cubes build by the side beams compared to the center cubes. On the other side an additional effect leading to inhomogenites is visible. Yet a correlation of focus error and the density of the cubes could not be supported with the current data. While the influence of the beam splitter on the center beam is neglectable, the inherent optical errors of the system must be compensated for the usability in future applications. Therefore, in the future, compensation strategies for power and focus errors need to be tested. This requires a deeper understanding of the separate influences of the different error inputs which are going to be the contents of future experiments.

References

Büsing, L.; Eifel, S.; Loosen, Peter (2014): Design, alignment and applications of optical systems for parallel processing with ultra-short laser pulses. In: Frank Wyrowski, John T. Sheridan, Jani Tervo und Youri Meuret (Hg.): Optical Modelling and Design III. SPIE Photonics Europe. Brussels, Belgium, Monday 14 April 2014: SPIE (SPIE Proceedings), 91310C.

Galbusera, Francesco; Caprio, Leonardo; Previtali, Barbara; Demir, Ali Gökhan (2023): The influence of novel beam shapes on melt pool shape and mechanical properties of LPBF produced Al-alloy. In: Journal of Manufacturing Processes 85, S. 1024–1036. DOI: 10.1016/j.jmapro.2022.12.007.

Heeling, Thorsten (2018): Synchronized Two-Beam Strategies for Selective Laser Melting. dissertation. ETH Zurich, Zurich. Online verfügbar unter https://doi.org/10.3929/ethz-b-000270330.

Hofmann, Oskar; Stollenwerk, Jochen; Loosen, Peter (2020): Design of multi-beam optics for high throughput parallel processing. In: Journal of Laser Applications 32 (1), S. 12005. DOI: 10.2351/1.5125778.

Lantzsch, T.; Westphalen, T.; Tenbrock, C.; Traub, M.; Haefner, C. L. (2021): Laser Powder Bed Fusion of Stainless Steel 316L Using a Flexible Dual Fiber Laser Array. Unter Mitarbeit von The University of Texas at Austin. In: University of Texas at Austin (Hg.): 2021 International Solid Freeform Fabrication Symposium. Austin.

Molotnikov, Andrey; Kingsbury, Alex; Brandt, Milan (2021): Current state and future trends in laser powder bed fusion technology. In: Fundamentals of Laser Powder Bed Fusion of Metals: Elsevier, S. 621–634.

Slodczyk, Marcel; Ilin, Alexander; Kiedrowski, Thomas; Bareth, Thomas; Ploshikhin, Vasily (2021): Spatter reduction by multi-beam illumination in laser powder-bed fusion. In: Materials & Design 212, S. 110206. DOI: 10.1016/j.matdes.2021.110206.

Sinico, Mirko; Metelkova, Jitka; Dalemans, Thibaut; Thijs, Lore; van Hooreweder, Brecht (2022): High speed laser powder bed fusion of M789 tool steel with an optimized 120 µm layer thickness approach. In: Procedia CIRP 111, S. 162–165. DOI: 10.1016/j.procir.2022.08.141.

Tsai, Chun-Yu; Cheng, Chung-Wei; Lee, An-Chen; Tsai, Mi-Ching (2019): Synchronized multi-spot scanning strategies for the laser powder bed fusion process. In: Additive Manufacturing 27, S. 1–7. DOI: 10.1016/j.addma.2019.02.009.

Yu, Kai-Sheng; Cheng, Chung-Wei; Lee, An-Chen; Jhang Jian, Wei-You; Chang, Wen-Cheng; Chang, Tsung-Wei; Tsai, Mi-Ching (2022): Additive manufacturing of NdFeB magnets by synchronized three-beam laser powder bed fusion. In: Optics & Laser Technology 146, S. 107604. DOI: 10.1016/j.optlastec.2021.107604.