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Development of a centrifugal laser powder bed fusion system for additive manufacturing

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Abstract

Due to the limited production rates of AM technologies, like PBF-L, the market and investment hype of AM has come to the slope of enlightenment, moving towards the plateau of productivity.
To further increase the diversity of AM machine designs and to solve limitations of conventional PBF-L the researchers of Fraunhofer IPT have rethought the kinematics of PBF-L machines. Inspired by centrifugal casting the metal powder is held on a circular track with high angular velocities causing a centrifugal acceleration of the particles in the powder bed, that overcomes gravitation. The laser optics is centered in the rotational axis melting the high velocity particles.
Process limitations are caused by the tradeoff between stabilized powder distribution and limited scanning speed. To increase processability and allow scalability the independent rotation of laser beam and powder bed were installed. This paper shows the development of a first prototype and initial process trials.

Keywords: laser powder bed fusion; rotation; centrifugal acceleration; additive manufacturing

1. Introduction

Additive Manufacturing (AM) is an innovative production method that fundamentally redefines how components are manufactured. Unlike traditional manufacturing techniques that involve removing or forming material, such as machining or molding, AM generates components by adding material. This process allows for the generating of three-dimensional (3D) structures directly from digital Computer-Aided Designs (CAD) files, making it an adaptable and versatile solution for modern manufacturing. AM involves the layer-by-layer construction of 3D-components, where each two-dimensional (2D) layer is built upon the previous one. AM is suitable for a wide range of materials, including plastics, metals, ceramics, especially high-strength materials. This versatility enables manufacturers to select the most appropriate material for each specific application, resulting in optimized product performance and functionality. By leveraging different material properties, AM can be used in different industries, including automotive, aerospace, medical, turbomachinery and tooling. (Gebhardt 2016)

In advanced manufacturing, AM offers several significant benefits, such as complexity for free, where the production of complex geometries does not acquire additional costs, making it economically viable to create component designs that would traditionally require expensive tooling. Additionally, AM allows lightweight for free, meaning reducing the mass of structures without compromising strength, by only generating material joints at tribologically optimized structures, which is particularly valuable in industries such as aerospace. Furthermore, the ability to customize components and achieve an individualization for free, easily allows manufacturers to meet specific customer requirements without the need for extensive retooling or setup changes. AM processes are resource-efficient, minimize material waste and energy consumption compared to traditional manufacturing methods, while showing a high potential for digitalization and facilitating the implementation of Industry 4.0 principles. (Springer 2015) (Gebhardt 2016)

The most developed technologies for metal AM are Powder Bed Fusion Technologies (PBF), which use different energy sources such as Laser Powder Bed Fusion (PBF-L) and Electron Beam Melting (EBM), involving fusing metal powder layers.

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But also, Direct Energy Deposition (DED) technologies are often used for metal AM allowing the repair and addition of material to existing components through a focused energy sources like lasers. The utilized laser energy melts either wire or powder materials. Therefore, these technologies are either called Wire-based Laser Metal Deposition (wLMD) or Powder-based Laser Metal Deposition (pLMD). A non-fusion technology for metal AM is the Binder Jetting (BJ) that uses a liquid binder to bond powder particles before subsequently sintering them to create a solid part. (Gebhardt 2016) (Springer 2015)

The market for metal AM has experienced steady growth over the past 25 years, with a global market volume of approximately 5.26 billion US-Dollar in 2023. By 2033, this figure is expected to rise to up to 19 billion US-Dollar, driven primarily by PBF-L technology, which holds over 50% of the market share. The Compound Annual Growth Rate (CAGR) for metal AM is estimated at 13.9%, indicating robust demand for metal AM solutions. The most significant markets for metal AM are in Europe, North America and Asia. (Spherical Insights 2025)

2. State of the Art and Research

2.1. State of the Art for Laser Powder Bed Fusion

As described in the previous chapter PBF-L is the most relevant technology for AM of metallic components. Not only has PBF-L the highest technology share in the market, annually around 1,500 PBF-L machines are sold across the world. The PBF-L process a layer-by-layer process where metallic or ceramic powders are selectively molten by laser radiation. This 3D printing process generates components by scanning the laser on a 2D powder bed, which is linearly descending. While the powder bed is defined along the x- and y-axis of a cartesian coordinate system, the descending powder bed represents the building direction or z-axis. The powder is laying in a calm state and is not experiencing any kinetic energy. The exclusive moment on the 2D surface comes from the scanning vectors of the laser scanner. Those scanning vectors are based on the scan paths and are defined in the pre-processing of PBF-L. During this pre-process the CAD-model of the component to be printed is sliced in layers and transferred into digital process data for the PBF-L machine. The in-process of PBF-L is cyclical as it can be seen in figure 1. (Gebhardt 2016) (Over 2003)

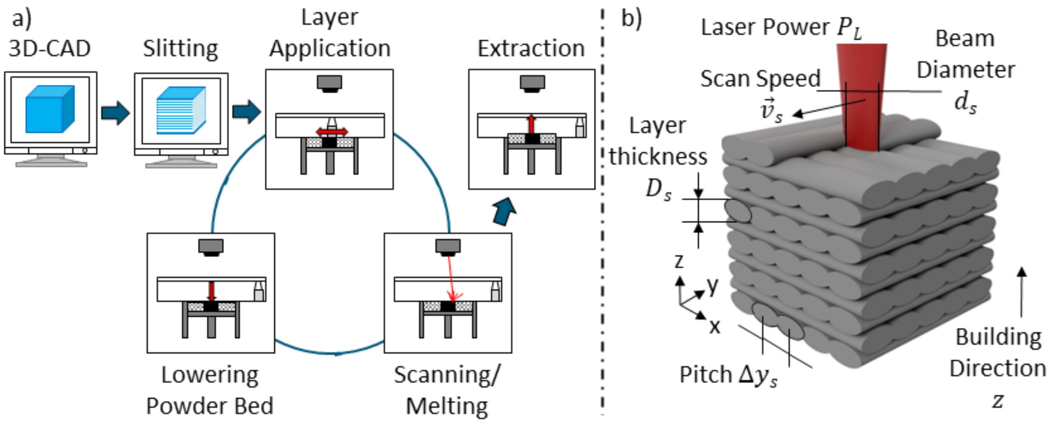


Fig. 1. (a) cyclical process of PBF-L including the digital pre-process and component extraction after (Gebhardt 2016);
(b) overview visualization of process parameter for PBF-L (Over 2003)

In between each scanned layer the powder bed in the building chamber is lowered and a new layer of the powder is applied before the next scanning cycle starts. The building chamber is filled with a global inert gas atmosphere to prevent the material from oxidation and to transport fumes or spatters from the welding process away from the laser beam. Depending on the used beam diameter d_S and the thickness of the powder layers D_S, PBF-L can be used to generate high resolution parts. As also shown in figure 1 further parameters used to define a PBF-L process are the Laser Power P_L, the scan speed $\vec{v}_s$ and the pitch Δy_S, which is the distance between two scan vectors.

Those parameters of PBF-L can be summarized in the term of volumetric energy density E_V which is defined to be the amount of energy applied per powder volume. A E_V that is used to generate metallurgically dense parts from a powder alloy, is often considered to reproduce consistent results. To calculate E_V the following formula (1) can be used. (Meiners 1999)

$$E_V = \frac{P_L}{\vec{v}_s \cdot \Delta y_s \cdot D_s} \tag{1}$$

For the calculation of E_V the output power of the laser is relevant, not the amount of absorbed power by the powder. Therefore, the scalability and reproducibility across different systems are not necessarily given for E_V. Meaning that an increase in laser power, doesn't necessarily allow an increase in scan speed, pitch or beam diameter at the same rate. Nor does the same E_V guarantee the same results if different PBF-L systems are used. Changes in the system or the process quickly lead to a loss in component quality due to defects, like weld spatter, gas inclusions or incompletely melted powder particles, limiting the scalability of the process and the increase in effective build rate. For this reason, PBF-L is up to today rarely used in high-volume production. The PBF-L process is limited in a tension triangle of build rate, build quality and build resolution, managing to achieve the optimum in not more than two of those. (Gebhardt 2016) (Over 2003) (Meiners 1999)

2.2. State of Research for Laser Powder Bed Fusion

The previous chapter shows that PBF-L, though it has a high potential for a wide industrial use, is only used in rapid-prototyping and small-series manufacturing. This led to an end of the hype and the high expectations, as it can be seen for many AM technologies. And after this disillusionment according to Gartner, the slope of enlightenment is expected to follow, where we are right now. Along this slope research and development is trying to deliver scalability approaches and may overcome the physical boundaries limiting PBF-L. The following table 1 gives an overview on recent research on PBF-L.

Table 1. Literature matrix giving an overview on latest works on PBF-L

		22 ANSA	23 BABA	22 BARE	23 BENE	20 BIND	22 BRAN	24 CAGL	22 CHMI	22 CHOU	24 COZZ	17 EIBL	21 FISC	21 GHAN	21 GU	05 HAUS	23 KANG	22 KAPP	22 LANG	21 LANT	20 LE	21 OLLE	21 PAPA	22 ROLI	22 SALE	21 SANC	24 SANC	22 SCHM	21 SCHN	22 SCHU	24 SOLA	22 STEN	20 STIT	19 TENB	20 TENB	21 TYRA	20 UHLM	22 VORO	24 WANG	21 YAVA	23 ZHAN
Pre-Process	Predictive Modelling		X																				X											X							
	Process Design																X	X			X		X						X	X		X					X			
	Process Chain																	X					X							X		X								
	Automation					X												X																		X					
	Structural optimization															X	X				X					X	X													
In-Process	Process development		X		X	X	X	X	X	X	X		X		X		X	X		X				X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
	Process simulation									X				X	X							X								X			X							X	
	Multi-Material			X		X									X														X												
	Material testing				X			X	X	X						X								X	X			X									X			X
	Process monitoring	X				X	X						X								X				X			X								X	X				
	Machine learning	X	X																		X																				
Post-Process	Digital-Twin						X																X																		
	Heat treatment								X																						X										
	Component qualification																						X		X											X				X	
	Economic efficiency																																X						X		
System technology	Powder feed system			X												X																									
	new machine concept											X				X																			X				X		
	Multi-Beam/ Multi-Scanner							X				X														X									X						
	Beam Shaping									X	X																X					X		X							
	Beam Sources							X				X					X			X												X									

(Ansari et al. 2022) (Babakan et al. 2023) (Bareth et al. 2022) (Benedetti et al. 2024) (Binder et al. 2020) (Brandau et al. 2022) (Caglar et al. 2024) (Chmielewska et al. 2022) (Chouhan et al. 2022) (Cozzolino et al. 2024) (Eibl et al. 2017) (Fischer et al. 2021) (Ghannouchi et al. 2021) (Gu et al. 2021) (Hauser et al. 2005) (Kang et al. 2023) (Kappe et al. 2022) (Langer et al. 2022) (Lantzsch et al. 2021) (Le und Quinsat 2020) (Olleak und Xi 2021) (Papacharalampopoulos et al. 2021) (Rolinck et al. 2021) (Salehi et al. 2022) (Sanchez et al. 2021) (Sanchez et al. 2024) (Schmeiser et al. 2022) (Schneck et al. 2022) (Schuh et al. 2021) (Solanki et al. 2024) (Stengel et al. 2022) (Stittgen et al. 2021) (Tenbrock et al. 2019) (Tenbrock et al. 2020) (Tyralla und Seefeld 2021) (Uhlmann et al. 2020) (Voropaev et al. 2022) (Wang et al. 2024) (Yavari et al. 2021) (Zhang et al. 2023)

The majority of research works focuses on in-process related improvements, like simulation-based investigations or advanced process development to explore the physical process limits. Furthermore, improvements of for pre- or post-processing like process automation, digitalization or enhanced process design, help to reduce processing times. Conducted research works focusing on system improvements mainly focus on enlarging systems, increasing the number of scanners or number of beams, shaping the beam or testing different beam sources. Only four papers conduct work on the machine concept of PBF-L. These four papers will be described as follows. Eibl et al. propose a new approach for PBF-L focusing on a new machine concept, as well as innovative beam sources and optical systems. Furthermore Eibl et al. introduces a single-mode laser source operating at 515 nm, which enhances energy efficiency and allows for better processing of highly reflective materials like silver, gold, and copper. In addition, an open-chamber concept that maintains local shielding gas flow, enabling larger build envelopes while achieving part densities greater than 99.5%. Furthermore, a multispot array, which utilizes multiple fiber-coupled diode lasers is introduced. This method significantly increases melting rates and exposure speeds, achieving part densities of 99.98%. The paper emphasizes the feasibility of these alternative exposure concepts, which not only reduces costs but also provides greater scalability and flexibility for PBF-L processes, paving the way for future research on optimizing spot arrangements for materials prone to cracking. (Eibl et al. 2017)

A quite similar approach is found in Tenbrock et al. This paper investigates the impact of using multiple laser scanner units in PBF-L on part quality. While the use of multiple scanners can significantly enhance productivity, the study identifies potential defects arising from the interaction between the laser beams and the plumes ejected from adjacent melt pools. Experiments were conducted using a gantry-based PBF-L prototype machine equipped with five laser scanners and a camera system to monitor plume propagation. The results indicate a correlation between void formation in parts and the plume patterns from neighboring melt pools. Depending on the used operating mode, either the jump-and-shoot mode or the on-the-fly mode, the processing head either remains stationary during exposure or experience synchronized movement. Findings reveal that in the jump-and-shoot mode, downstream specimens are adversely affected by the plume of the upstream specimens, particularly at specific distances and angles relative to the gas flow. In contrast, the on-the-fly processing demonstrated similar effects, but with a potential increase in part density due to improved gas flow dynamics during processing. The study concludes that strategic adjustments in multi-scanner processing can mitigate laser-plume interactions, ensuring consistent part quality while maximizing productivity in PBF-L applications. (Tenbrock et al. 2020)

Hauser et al. present a novel technique for rapid manufacturing via PBF-L aimed at improving the efficiency. The innovation lies in the method of powder layer deposition, where layers are continuously deposited in a spiraled manner from a stationary hopper onto a rotating build drum. This configuration allows for simultaneous powder delivery and processing, eliminating delays associated with traditional layer-by-layer methods. Hauser et al. utilize a 100 W Nd:YAG laser to selectively melt stainless steel and cobalt-chrome powder, focusing on factors influencing build rate and strategies for creating axis-symmetric thin and thick-walled cylinders. Experimental results indicate that the build rate for thin-walled structures is primarily affected by the tangential movement of powder particles when frictional forces are insufficient to accelerate them along a curved path. Notably, the phenomenon of melt pool balling diminishes with multiple layer builds due to effective re-melting and infilling. The paper emphasizes the potential of the spiral-growth manufacturing approach to produce high-density parts efficiently, while providing insights into melt behavior under various scanning conditions. The study concludes that while current build rates range from 5 mm^3/s to 8 mm^3/s, further improvements in scanning strategies and laser power could enhance production rates and part quality. (Hauser et al. 2005)

A planarly rotating powder bed approach is also subject in Wang et al. The authors highlight that while PBF-L is adept at creating complex geometries with a variety of metals, its production rates, measured in hundreds of grams per hour, fall short of the kilograms per hour achieved by other processes like forming or casting. To address this gap, the paper proposes a new scalable architecture that could potentially increase production rates through the integration of rotary table kinematic arrangements, a greater number of simultaneously operating lasers, reduced laser optic sizes, improved scanning techniques, and optimized toroidal build plate sizes. The study includes a productivity analysis relevant to synchronous reluctance motors, particularly for the electric vehicle industry, emphasizing the need for advancements in the range of printable alloys. By comparing traditional cartesian systems with rotary architectures, the authors discuss the advantages of rotary systems, such as simultaneous layer fabrication and improved laser duty cycles, which could lead to significant productivity improvements. The paper concludes that while current laser based rotary systems with have shown promising results, further enhancements in laser technology and system design are necessary to achieve mass production levels that could make PBF-L a viable option for industrial applications. (Wang et al. 2024)

None of the described papers fundamentally question the kinematics in the machine concepts for PBF-L. The researchers at Fraunhofer IPT have, inspired by centrifugal casting, come up with a fundamentally new machine concept rejecting the planar layer system and creating new process variables influencing the metal fusion process.

2.3. Centrifugal Casting

The process of centrifugal casting was patented in England in the 19th century but has been used in craftsmanship since before the Middle Ages. Throughout the 20th century scaled and more industrialized techniques were developed. Today, centrifugal casting processes have become the standard in the manufacturing industry for producing rotationally symmetric components such as pipes. The influence of centrifugal force on the casting process is the key distinguishing factor. The horizontal centrifugal casting method is widely used. In this method, molten metal is led into a rotating, cooled mold through a refractory pouring channel. The molten metal adopts the surface speed of the mold over time, and the constant rotation generates sufficient centrifugal acceleration to overcome gravity. Consequently, the molten metal is distributed along a circular path, solidifying due to heat conduction into the mold. Centrifugal casting includes high pouring pressure, which optimally fills the mold and distributes the molten metal even in small contours. The proportional dependencies of the casting pressure are shown in formula (2). (Gorny 1977) (Bühring-Polaczek et al. 2014)

$$p_{Cast} \sim \rho_{Melt} * r_{Melt} * \omega_{Melt}{}^{2} \qquad (2)$$

The casting pressure p_{Cast} directly proportional to the density ρ_{Melt}, the radius r_{Melt} and the square of the angular velocity ω_{Melt} of the melt. This formula is closely related to dependency of the centrifugal acceleration and the rotational speed. Although dense particles accumulate at the outer surface, gas pores and defects tend to gather at the inner surface of the rotation. The rapid directional cooling and solidification of the molten metal reduce shrinkage and microporosity while potentially causing micro- and macro-segregation in the structure. Despite challenges of segregation and fine porosity at the inner rotational surface, the centrifugal casting process is characterized by low pouring temperatures and a directed, dense microstructure. Compared to gravity casting, centrifugal casting offers higher dimensional accuracy, reduced machining allowances, favorable casting technology, and the ability to produce composite materials. (Xu et al. 2021) (Dong et al. 2020)

3. RotaPrint Approach and Model

The RotaPrint approach by Fraunhofer IPT sets the powder bed in rotation around a horizontal axis. The resulting centrifugal acceleration keeps the powder particles on a circular path attached to the building drum. Centred in the circular path is a stationary laser optical head which is axially movable and is facing downwards. The powder particles pass the laser focus and get molten. Therefore, the scan speed of conventional PBF-L as main process speed, is replaced with the circumferential speed of the rotating powder. The RotaPrint process has, just like conventional PBF-L, a cyclical sequence, building up layer-by-layer. However, in principle the productive and nonproductive steps can be parallelized. This cyclical sequence is shown in figure 2.

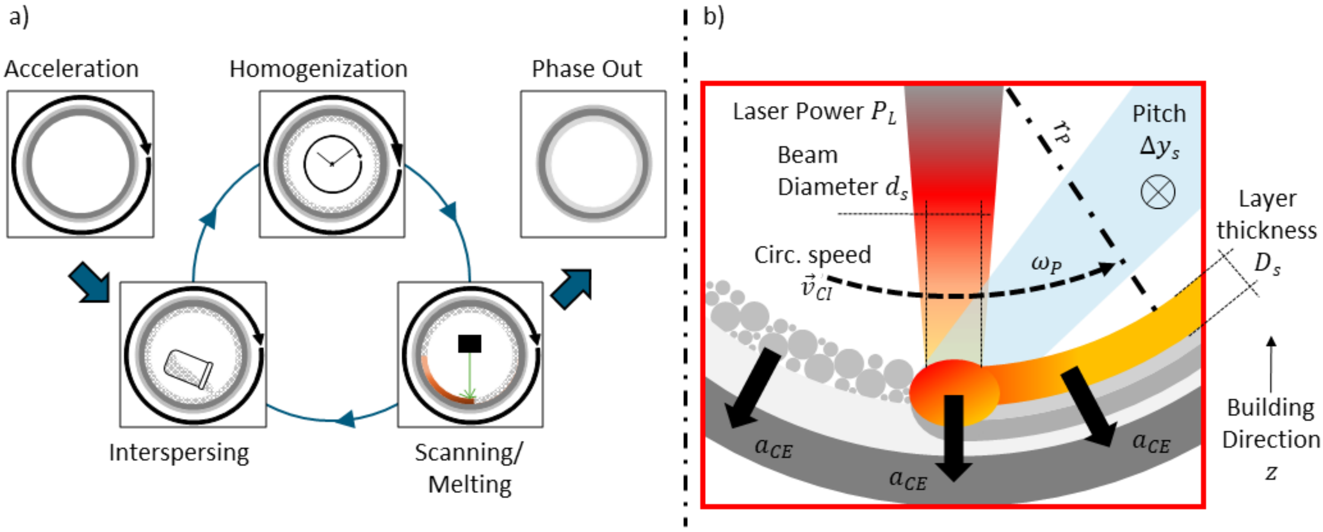


Fig. 2. (a) cyclical process of PBF-L including the digital pre-process and component extraction after GEBH;
(b) overview visualization of process parameter for PBF-L

Besides the cyclical sequence, figure 2 also shows the process parameters of the RotaPrint approach. Besides the known parameters from conventional PBF-L, like beam diameter d_S, layer thickness D_S, Laser Power P_L and the pitch Δy_S, there are new parameters like the resulting circumferential speed $\vec{v}_{CI}$ and the centrifugal acceleration a_{CE} of the powder. Both parameters depend on the angular velocity ω_P and the radius of the rotation r_P. The formulas for the a_{CE} and $\vec{v}_{CI}$ are shown in (3) and (4).

$$a_{CE} = {\omega_P}^2 * r_P > g \quad (3)$$

$$\vec{v}_{CI} = \omega_P * r_P \quad (4)$$

The dependency of a_{CE} and $\vec{v}_{CI}$ on the ω_P and r_P as seen in formula (3) and (4), leads to a key trade-off for the technology. On the one hand ω_P and r_P shall be as high as possible to maximize a_{CE}, overcome gravity and stabilize the powder bed on the circular path. On the other hand, ω_P and r_P are limited due to the minimum required interaction time of laser and powder particles. If the powder particles pass the laser too fast, the cumulated absorbed energy into the particles is too small, causing the powder not to form a melt pool. This can be also seen in the adapted equation for E_V of RotaPrint. With increasing $\vec{v}_{CI}$ the resulting E_V decreases. The calculation of E_V for RotaPrint, including $\vec{v}_{CI}$ as main process speed, can be seen in formula (5).

$$E_V = \frac{P_L}{\vec{v}_{CI} \cdot \Delta y_s \cdot D_s} \quad (5)$$

To further investigate the effects of the high process speed $\vec{v}_{CI}$ and the behavior of the powder under the influence of a_{CE}, the researchers of Fraunhofer IPT have designed a prototype of the RotaPrint machine and conducted initial tests, as shown in the following chapter.

4. Machine Setup and initial Testing

The key element of the prototype consists of a rotatable building drum for the rotation of the powder bed. Due to the geometry of this building drum, the effective building area increases by factor π, while the machine footprint stays consistent. With in the building drum is a stainless-steel substrate ring inserted that is centred by spring-loaded thrust pieces. The purpose of this substrate ring is to form a base for the components to be generated and to remove them from the building drum. The substrate ring has an inner diameter of approximately 406 mm. This diameter was chosen due to the available commercial ring sizes and the achievable values for a_{CE} and $\vec{v}_{CI}$. Figure 3 shows the RotaPrint prototype.

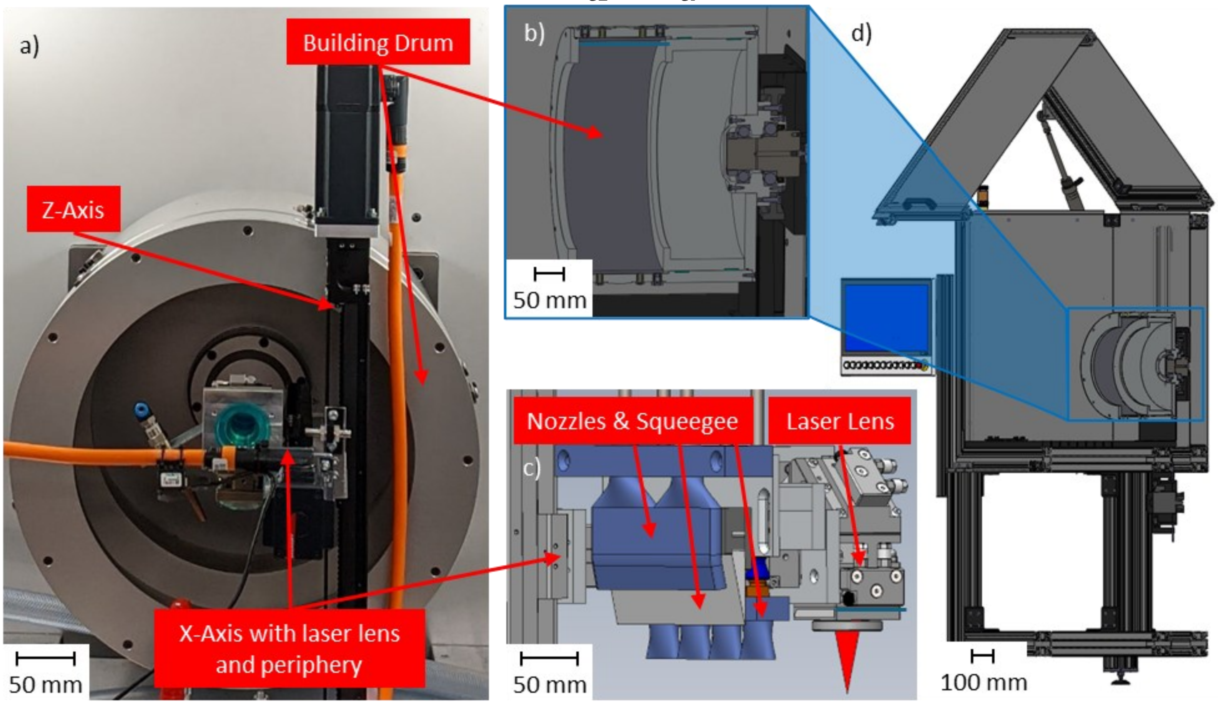
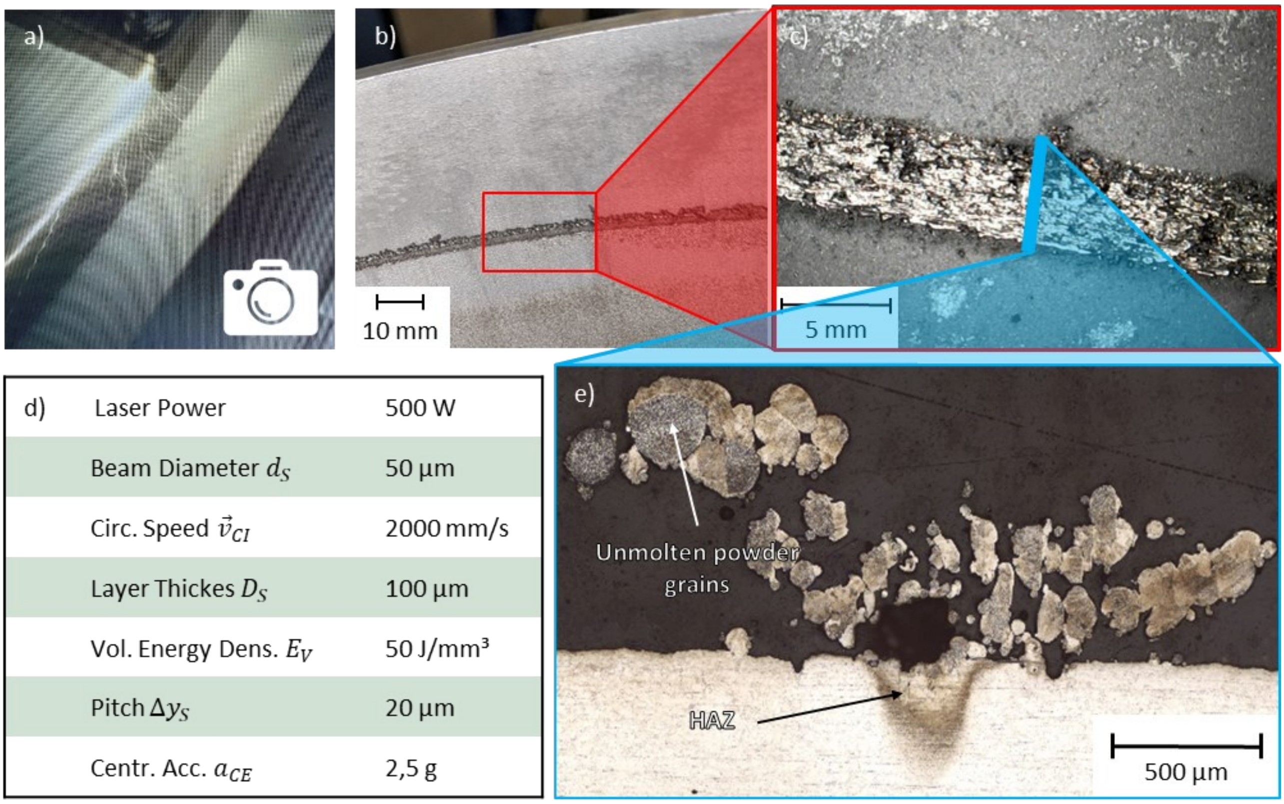


Fig. 3. (a) picture of the RotaPrint test rig including axis system and laser optical head; (b) Close up CAD model substrate ring and centered bearing; (c) CAD model of nozzle and squeegee periphery on the axis system; (d) CAD model of RotaPrint test rig including building drum.

Figure 3 show the building drum and the axis system consisting of an axial X-axis and a radial Z-axis, which is in front of the building drum. The X-axis generates the hatch with each rotation of the building drum by moving the laser head through the drum, parallel to the rotational axis. On the backside of the X-axis the cross-jet nozzle, the powder feeding nozzle and a squeegee are mounted. Meanwhile the Z-axis adjusts the working distance of between the laser head and the powder bed and carries the X-axis. Layer by layer the position of the Z-axis is adjusted to maintain the focal point of the laser on the level of the powder bed. Both axes are spindle driven and the axis pair is removable, allowing for easy substrate changes within the building drum.

The drum rotation is generated via a belt drive and a motor fixed underneath. The angular velocity of the drum is set and held constant for each layer. Following the commissioning of the test rig, initial process trials were executed. An exemplary result including the used parameters, can be seen in figure 4.



d)		
	Laser Power	500 W
	Beam Diameter d_S	50 µm
	Circ. Speed $\vec{v}_{CI}$	2000 mm/s
	Layer Thickes D_S	100 µm
	Vol. Energy Dens. E_V	50 J/mm³
	Pitch Δy_S	20 µm
	Centr. Acc. a_{CE}	2,5 g

Fig. 4. (a) picture of process camera; (b) picture of generated track; (c) close-up of generated track; (d) overview on parameters used to generate the track; (e) microscopic image of the etched cross-section

The result shown in figure 4 indicates that the powder material can not be fused to a metallurgical dense material. In the top-view on the generated track one can see a rough and uneven surface, comparable to laser sintered components. It can be observed that some powder grains were molten, and some remain unmolten. The substrate indicates a clear heat input or heat-affected zone, which is smaller than the track width.

This result indicates a lack of energy input and an uneven energy distribution causing an instable fusion of the powder bed. The reason for this is the short interaction time between the laser and the powder grains, which results from the high angular and circumferential speed. Another explanation is an uneven powder distribution along the substrate depth or an uneven concentricity of the substrate, causing inconsistent interaction conditions for the energy input. On the one hand this leads to local defocusing of the laser on the powder bed. On the other hand, local differences in the powder layer thickness can occur. Thicker powder layers shield the laser energy from the substrate, only melting powder grains with no metallurgic bond to the substrate.

Critical for the success of the technology is the limitation of energy input caused by the necessary rotational speed for a given laser power. To overcome the limitation and interdependency between angular acceleration and interaction time the system was adapted to enable rotation of the laser head. (Janssen et al. 2021)

5. Rotating Laser Head and improved process model

To increase the exposure time of the powder particles to the applied energy, either the effective distance along the energy input must be increased or the relative velocity between the powder material the energy source needs to decrease.

At first a pre-heating was developed that utilizes two infrared (IR) radiators. Pre-heating of the powder bed is commonly employed in conventional powder bed processes or other AM processes, particularly when processing high-strength materials. The powder bed is heated to temperatures below melting point, ensuring that the laser only needs to apply enough energy to create a melt pool in the powder. This approach used an extra half of the rotational surface to apply energy into the powder material.

A second and more promising adjustment was enabling rotational movement of the laser beam. In this setup the rotating laser and the powder bed have independent circumferential speeds, which results in an adjustable relative scanning speed. Decoupling the dependency between process speed and centripetal acceleration allows minimal relative speeds even at high angular velocities, allowing for maximization of interaction time with the laser beam. While the calculation of the centrifugal acceleration is not affected by this adjustment, the equations for the circumferential speeds are presented in the following formulas (6), (7) and (8).

$$\vec{v}_{CI\_L} = \omega_L * r_L \tag{6}$$

$$\vec{v}_{CI\_P} = \omega_P * r_P \tag{7}$$

$$\vec{v}_{CI_{Rel}} = \vec{v}_{CI_L} - \vec{v}_{CI_P} = (\omega_L - \omega_P) * r_P \qquad \mathit{if} \qquad \mathrm{r_P} = r_\mathrm{L} \tag{8}$$

Formula (8) applies if r_P equals the radius of the laser rotation (r_L). Therefore, the rotational axis of the powder bed and the laser must match. The resulting relative circumferential speed ($\vec{v}_{CI\_Rel}$) is the difference of the laser circumferential speed ($\vec{v}_{CI\_L}$) and the powder circumferential speed ($\vec{v}_{CI\_P}$). With r_P being the radius for both rotational movements, $\vec{v}_{CI\_Rel}$ only depends on the difference between (ω_P) and the angular velocity of the laser beam (ω_L). Only if the difference of ω_P and ω_L remains the driving factor for the relative speed and the resulting interaction time between laser and powder, the influence of r_P can always be compensated. Consequently, this allows for a scaling of r_P and enlargement of the building drum. This enables an increased building area and reduce the surface curvature of the powder bed. The effect of the surface curvature on the generated components is not negligible. (Janssen et al. 2021)

To enable the adjustment as described above a new laser head was designed. Figure 6 shows the laser head for the rotation of the laser beam.

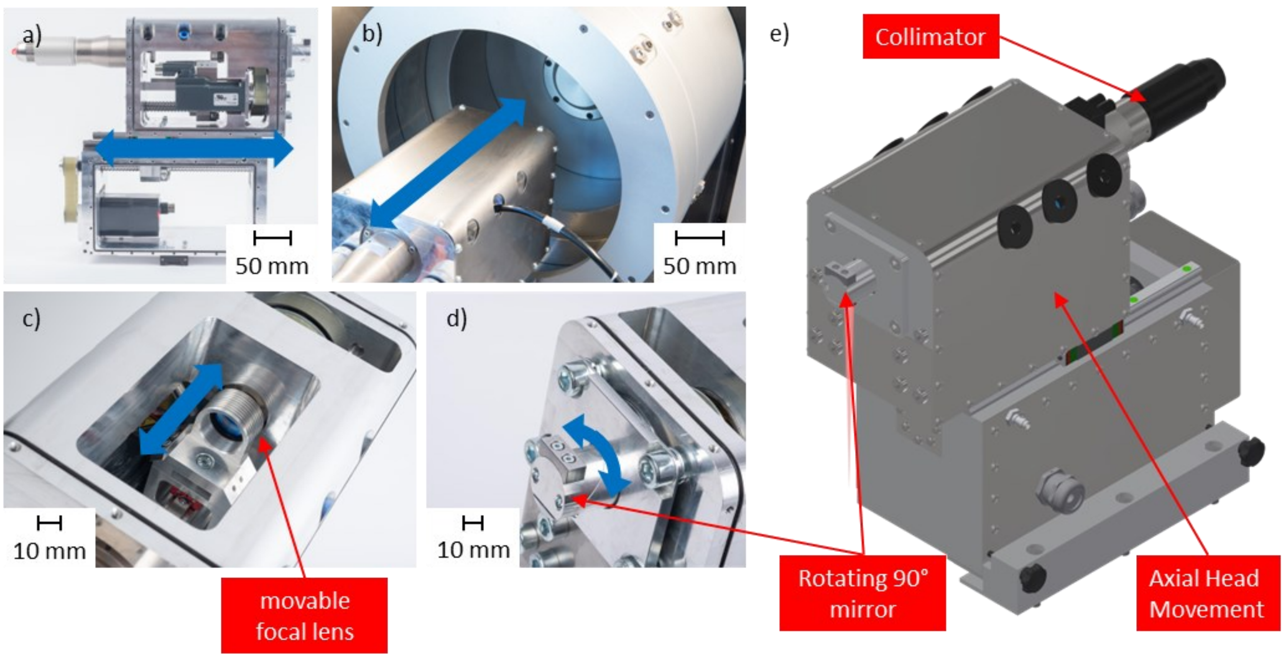


Fig. 5. (a) side view on the uncovered laser optical head; (b) integrated laser optical head in the RotaPrint test rig; (c) top view on the uncovered laser optical head including moveable focusing lens; (d) front view on the rotating laser lens; (e) full view on designed laser optical head as CAD

The laser head includes three basic kinematics, which are visualized in figure 6 as blue arrows. As in the old axis-setup, the optical head can be moved along the rotational axis through the drum to create the pitch. This axial movement can be seen in figure 6a and 6b. Besides the new rotation of the laser beam in clockwise or counterclockwise direction, also the radial movement to adapt the focal distance layer-by-layer must change. In the new laser optical head, a focal shift is designed to adjust the focal point on the powder bed without moving the optical head in building direction. The collimated beam is guided through the movable focal lens, seen in figure 6c. After passing the focal lens the beam is deflected 90° by a rotating mirror, seen in figure 6d. Since the focal lens is placed in front of the deflecting mirror, the movement of the focal length directly correlates with the radial movement of the focus point on the powder bed. The axial movement through the drum and the movement of the focal lens are spindle driven, while the rotation of the deflecting mirror is also realized via a belt drive and a motor.

The laser head for the laser beam rotation was successfully designed, integrated and tested for its functionality. Further process evaluations with the new adjusted system will be carried out in the future. Initial tests will focus on the testing of the powder behavior in the drum and the laser energy input into the substrate without the powder material before increasing process complexity by introducing single and multi-layer experiments.

6. Summary, Potentials and Outlook

The researchers at Fraunhofer IPT have come up with a disruptive kinematic for laser-based powder bed fusion processes to overcome the limiting boundaries of AM and conventional PBF-L. The new kinematic approach causes fundamental changes in the technology of the process and system technology. Enabling new process parameters, like centrifugal acceleration and circumferential speed, to affect the results of component quality and material properties. Centrifugal acceleration and circumferential speed are both based on angular velocity and rotational radius, leading to an elementary trade-off between high acceleration to stabilize the powder bed and a limited process speed to ensure enough energy input in the powder material. This trade-off has been confirmed in the initial testing of the prototype. The applied energy by the laser is only sufficient to partially bond the powder particles but does not fully fuse the material to a dense volume. Therefore, the process model was adjusted to decouple the dependency of centrifugal acceleration and circumferential speed. By setting the laser beam into angular rotation, the laser focal spot and powder bed each have an individual circumferential speed, along the circular path, resulting in a adjustable relative speed between each other.

The potential of this RotaPrint technology is particularly expected in the production of large rotational symmetrical components such as full layer rings, internally geared wheels or large bearing housings. By utilizing angle-dependent laser control, it is also expected to enhance the production of single prismatic components along the powder bed. The innovative drum geometry maximizes the usable surface area of the building chamber, leading to increased efficiency. Drawing parallels to centrifugal casting, this technology is expected to compress the powder grains, optimize gas flow within the chamber, and creating a strongly directional heat conduction in the material. Further influencing the melt pool dynamics and effectively shifting defects like pores or shrink holes towards the inner diameter. This simplifies post-processing or eliminate these imperfections. Consequently, it is anticipated that this technology will substantially increase the building rates of high-quality AM components. By controlling the centrifugal acceleration as main process gravitation, RotaPrint is promising for enabling 3D printing in a zero-gravity atmosphere, opening new frontiers for additive manufacturing in space.

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