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ИЗЫСКАНИЕ, ПРОЕКТИРОВАНИЕ, СТРОИТЕЛЬСТВО И МОНТАЖ ТЕХНОЛОГИЧЕСКОГО ОБОРУДОВАНИЯ ОБЪЕКТОВ АТОМНОЙ ОТРАСЛИ

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КОМБИНИРОВАННЫЕ ЛАЗЕРНЫЕ АДДИТИВНЫЕ ТЕХНОЛОГИИ ПРОИЗВОДСТВА ЛОПАТОК ТУРБИН СЛОЖНОЙ ГЕОМЕТРИЧЕСКОЙ ФОРМЫ

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Лазерный луч, как источник энергии все чаще используется в аддитивных технологиях изготовления деталей энергетического машиностроения. Одними из перспективных методов аддитивного производства являются технологии, основанные на лазерном сплавлении Laser Metal Fusion (LMF) и лазерной наплавке металического порошка Laser Metal Deposition (LMD). Использование порошковой ванны в технологии LMF позволяет синтезировать детали сложной геометрической формы. Недотатками LMF являются низкая скорость процесса, относительно небольшой размер изготавливаемой детали и существенные ограничения в использовании различных материалов порошков во время изготовления детали. Технология LMD напротив, реализует более высокие скорости выращивания детали с возможностью смены порошка во время процесса. Однако, технология LMD имеет существенные ограничения по сложности геометрической формы изготавливаемых деталей. Комбинируя возможности двух этих технологий можно добиться соответствующих преимуществ, а именно изготавливать детали сложной геометрической формы, большего размера и с высокими скоростями процесса. В работе рассмотрены особенности комбинированной лазерной аддитивной технологии на примере изготовления лопаток газовых турбин со сложной геометрической формой. Эффективность предлагаемой технологии подтверждает более чем 60% сокращение времени изготовления детали.

Ключевые слова: аддитивные лазерные технологии, селективное лазерное сплавление, лазерная наплавка лопатки турбин.

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INTRODUCTION AND STATE OF THE ART

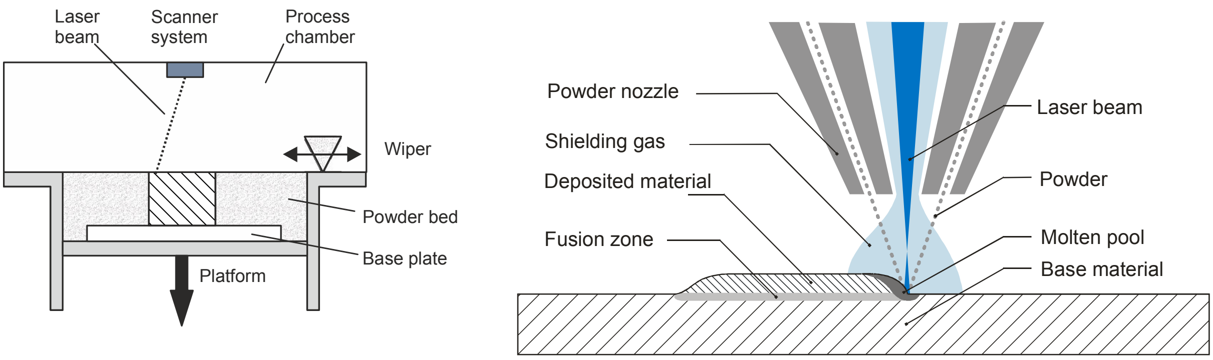
Today, the trend to individualized products and decreasing time to market, leads to an industrial demand for flexible manufacturing technologies [1]. These technologies have to be sustainable and resource-efficient, and have to allow the production of long-life capital goods. Additive manufacturing technologies offer high flexibility regarding complex design features and allow direct manufacturing from CAD-data without tooling, therefore saving time and costs [2]. Leading manufacturing companies are including additive manufacturing to their service portfolio. ZEISS offers support along the whole additive process chain from design till the finished product [3], and TRUMPF has recently entered the market with their own powderbed-based additive manufacturing machine TruPrint Serie 1000.

Additive processes gain in importance especially in the aviation industry, where the potential of lightweight structures to increase payload capacity and to decrease fuel consumption and pollutant emission is relevant.

Important laser beam processes for additive manufacturing are Laser Metal Fusion

(LMF) and Laser Metal Deposition (LMD). LMF is using a powder bed and based on three repeating steps. First, a thin layer of metal powder is placed on a platform with a mechanical coating system. In the second step, a focused laser beam selectively melts the top-most layer of the powder bed. And in the third step, the platform is lowered by the layer thickness and the cycle begins again. Typical layer thickness ranges from 30 µm to 50 µm, so complete parts usually consist of thousands of layers. Picture 1(a) shows the LMF process.

The LMD process is shown in picture 1(b). A molten pool is created on the surface by a laser beam. At the same time, powdery filler material is injected in the molten pool. After solidification, the filler material forms single weld beads. Multiple weld beads placed next to each other form layers or volumes.



Picture 1: (a) Laser metal fusion process; (b) Laser metal deposition process

Despite their ability to manufacture highly complex parts, the industrial applications of powder-bed based technologies like LMF are still limited because of low build-up rates. In order to improve the feasibility of additive manufacturing for industrial applications, it is necessary to improve manufacturing time for small and medium sized batch production. The Center for Digital Technology and Management in Munich describes an increased build-up rate as key driver for additive manufacturing in order to reach an expected market volume of €7.7 billion in 2023 [4]. In recent years, different methods for this purpose have been discussed and developed. One method are systems with higher laser power in order to melt multiple layers at the same time [5]. Another option are multi beam systems described in [6]. While an increased build-up rate was achieved, manufacturing time still remains too long for batch production.

LMF normally is restricted to the same powder for the whole build-up process. The need for more material flexibility drives current research activities. One option to modify material properties is creating different porosity levels, as described by Wegener from ETH Zürich in [7]. New materials are qualified by researches around the world, therefore increasing applications for powderbed-processes.

Instead of a powder-bed, Laser Metal Deposition (LMD) utilizes a powder nozzle for material delivery. Its application as additive manufacturing technology for Ti-6Al-4V and Inconel 718 is described in [8]. Material deposition for repair purposes and resulting mechanical properties are shown in [9] and [10]. In order to adjust process parameters for the additive manufacturing of a specific geometry, the relation of process parameters and bead geometry can be determined with design of experiments [11].

LMD offers the possibility to change the deposited material during the welding process. Scientists from the California Institute of Technology have shown that the production of multifunctional metal alloys with a strategically graded composition is possible, therefore mechanical and physical material properties can be adjusted for the respective application. This can be used for graded metal inserts in spacecraft panels [12].

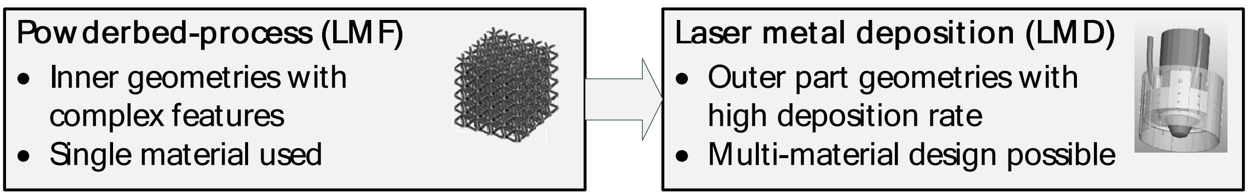
Although LMF and LMD are increasingly covered in scientific research, a combination of Laser Metal Fusion and Laser Metal Deposition has rarely been described. To the authors knowledge, only one publication describes laser cladding as repair technology for tools made by selective sintering [13]. Multiple layers crack free and strongly bonded with the substrate could be deposited, although porosity was observed. Therefore, [13] recommends a grinding process on the surface to reduce porosity in the clad.

A comparison of the two additive processes LMF and LMD is shown in table 1. Because of their respective features, a combined additive process chain has the potential to benefit from high structural complexity with LMF, while increasing build-up rates and material flexibility with LMD.

Table 1: Comparison of additive technologies

	Part dimensions	**Structural complexity**	**Substrate**	**Material flexibility**
Laser Metal Fusion	Limited by the process chamber	High, e.g. lattice structures	Flat surfaces	Same powder for the whole process
Laser Metal Deposition	Limited by the machine working area	Limited, e.g. walls	Arbitrary surfaces	In-process change of powder

The aim of this paper is the combination of both additive manufacturing technologies LMF and LMD. This novelty allows manufacturing of complex components with high build-up rates, while maintaining high dimensional accuracy in the complex part. For this purpose, the feasibility of LMF and LMD combination is described.



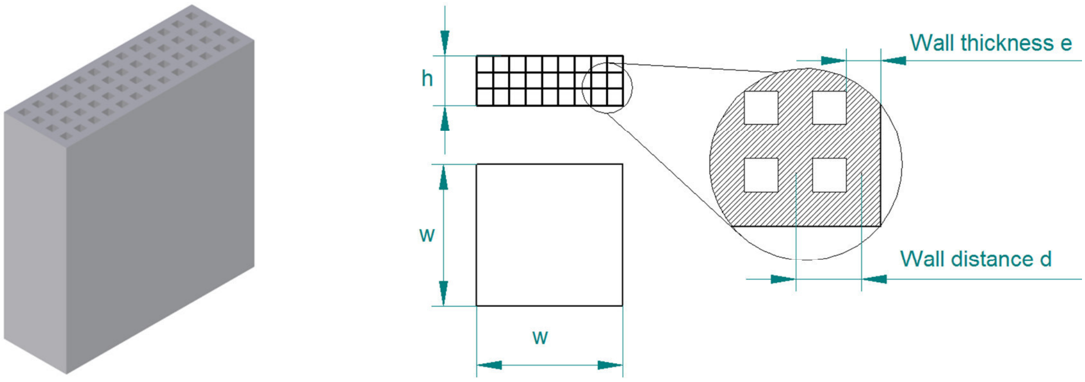
Picture 2: Combined additive manufacturing

EXPERIMENTAL

LMD is conducted with a TRUMPF TruDisk 2002 system and 3-jet powder nozzle. For LMF, the machine 250HL from SLM Solutions is used.

Lattice structures

In order to evaluate basic influences of the LMD process on a LMF substrate, different test geometries are manufactured with the combined process chain. The test geometries consist of lattice structures with different wall thickness, resulting in different stiffness and heat dissipation. Thereby typical LMF part features are represented in the substrate. Picture 3 shows the LMF substrate, and table 2 the variation of its wall thickness.



Picture 3: Test specimen manufactured with LMF

Table 2: Geometric dimension of test specimen

Number	Wall thickness in mm	Wall distance in mm	Height in mm	Width in mm
1	0.5	1.0	7.5	20.5
2	0.75	1.5	6.75	20.25
3	1	2	7	21
4	1	3	7	20

After LMF manufacturing, 10 layers of material are deposited with LMD on the specimen. No cooling break was made between the depositions of each layer. The process parameters are shown in table 3. The titanium alloy Ti-6Al-4V was chosen because of its susceptibility to heat tint, which allows to easily indicate thermal influence of the LMD process on the substrate. The geometrical influence regarding distortion is evaluated by comparing a 3D scan of the specimen before and after LMD welding.

Turbine blade:

Combined additive manufacturing is applied for the manufacturing of a turbine blade. First, a conventional turbine blade design is adjusted according to additive manufacturing design rules. The airfoil portion of the blade including its complex inner structures is built with LMF first. In the second step the fir-tree root of the blade is built with LMD employing two different parameter sets. One parameter set is optimized for high accuracy, while the second set is chosen in order to build massive volumes with a low number of layers. Every 5 layers cool down times around 3 minutes were made in order to prevent heat accumulation. The blade is manufactured from nickel-based alloy Inconel 718. The process parameters are shown in table 3. In order to evaluate build-up rates and potential economic benefits of combined laser additive manufacturing, the same blade is built with LMF only.

RESULTS AND DISCUSSION

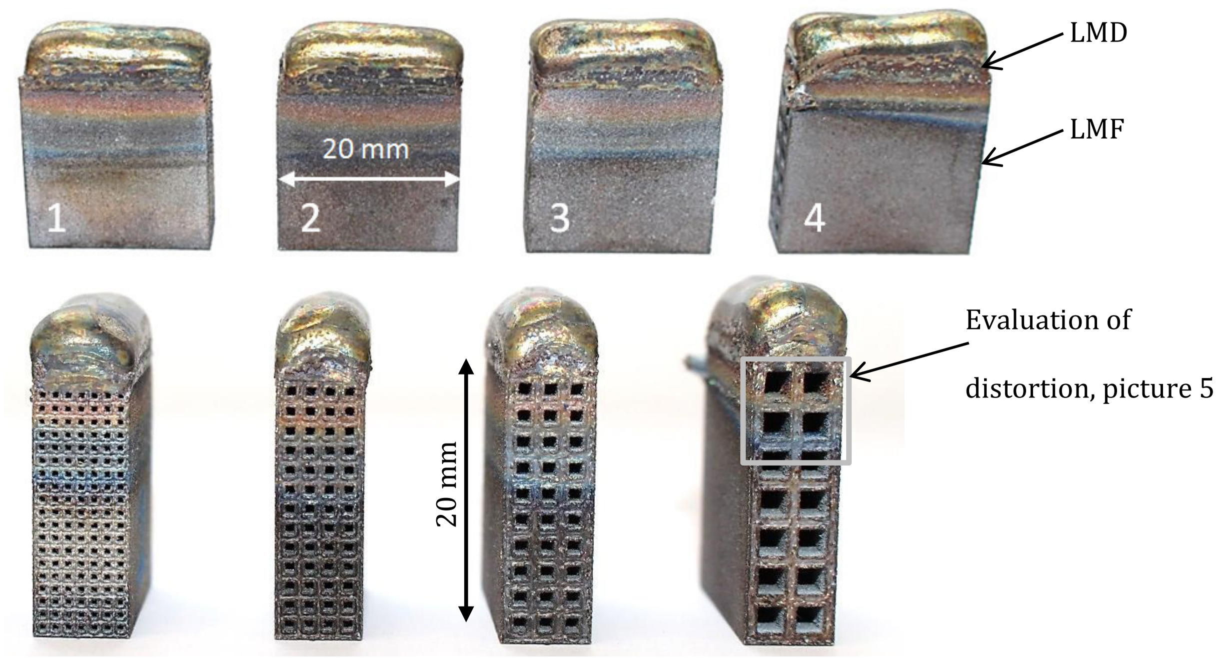
Test structures for LMF-LMD combination:

The test specimens after LMD material deposition are shown in picture 4. Geometries 1 to 3 have similar heat tint, while the heat tint in specimen 4 is confined in a smaller area closer to the LMD part. This difference can be explained by the part specific heat dissipation due to different wall thicknesses. The heat conduction for specimen 4 is along a width of

3 mm (3 walls with 1 mm thickness each), while the other specimen are considerably higher between 3.75 mm and 4 mm. The lower heat dissipation in specimen 4 leads to higher heat accumulation at the top and a smaller spatial extend of heat tint.

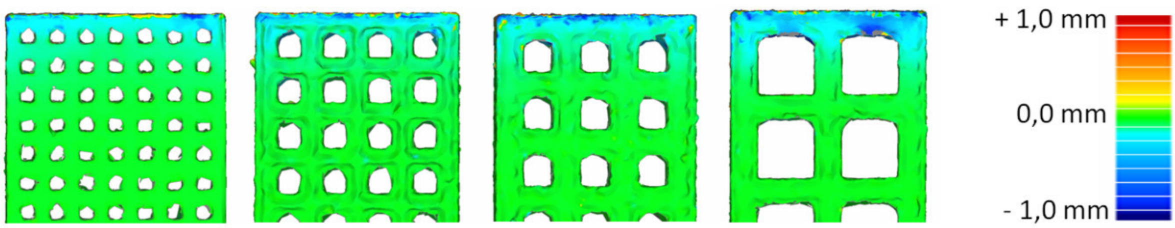
Table 3: Process parameters for test specimen and blade manufacturing

		Laser power in W	Velocity in mm/min	Spot diameter in mm	Powder mass flow in g/min
Test specimen Ti-6Al-4V	LMD	1000	1000	1.0	3.75
	LMF	275	975	0.1	-
Turbine blade Inconel 718	LMD volume	1000	600	1.0	6.5
	LMD high accuracy	800	800	1.0	6.5
	LMF volume	250	700	0.1	-
	LMF grid structure	150	350	0.1	-



Picture 4: Heat tint on test specimen after LMD deposition

Picture 5 shows the evaluation of geometric deviations after LMD welding based on the 3D scan. All four structures provide sufficient stiffness to prevent significant distortion due to LMD welding. Deviations are only visible along the edge and the contour, where substrate material is melted and geometric precision is lost after solidification.



Picture 5: Geometric deviation of LMF substrate after LMD welding, determined by 3D scan

These results from heat tint and geometric analysis can be applied to design the build-up process for the combined additive manufacturing in the following way:

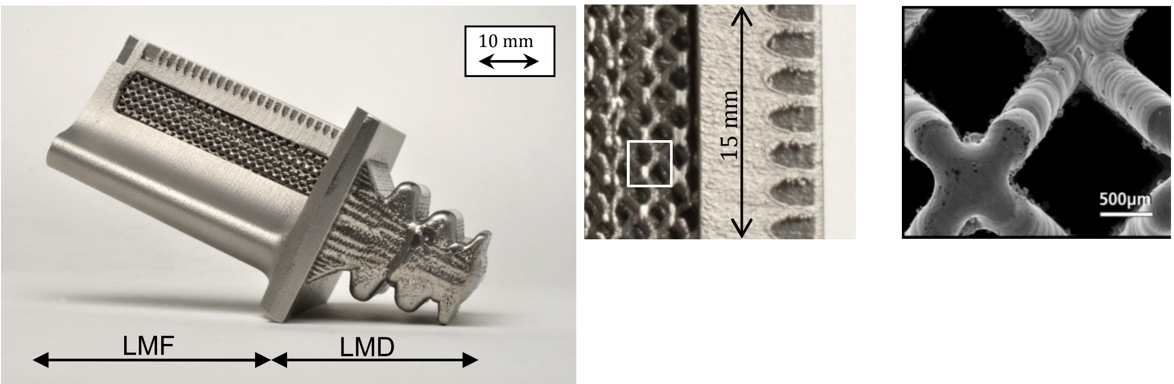
– In order to avoid heat accumulation resulting in heat tint, cool down times between layers should be made. It is necessary to account for individual part features regarding heat dissipation while designing the cool down times.

– Multiple LMD parameter sets should be applied during the build-up of a volume. Along the contour, a parameter set with low heat input and small melt pool seems favourably in order to reduce the influence on the edge of the LMF substrate. During the build-up of the inner volume, a parameter set with higher energy input and deposition rate can be chosen.

Both aspects are considered for the turbine blade manufacturing.

Turbine blade:

The turbine blade produced with combined laser additive manufacturing is shown in picture 6. In the detailed view of the lattice structures no cracks or deformations are visible. High geometrical accuracy was achieved for the complex trailing edge.



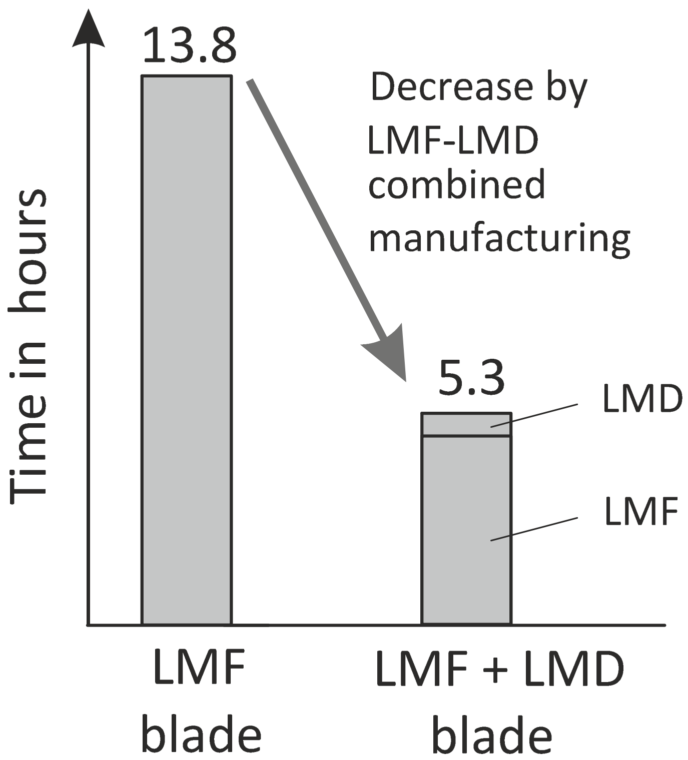
Picture 6: Turbine blade manufactured by LMF and LMD

The fir-tree root is built near net shape. Since this is a high precision part, further machining via CNC milling is required independently of the production method with LMF only or the combined laser additive manufacturing.

The possibility to include complex inner structures leads to higher functionality of turbine blades. Full material regions can be replaced with lattice structures, therefore a lighter design with sufficient stiffness can be achieved. Another advantage of lattice structures is a more effective heat exchange between cooling air and blade wall due to an increased surface-to-volume-ratio. The consumption of cooling air is reduced and thereby the degree of efficiency is increased.

A significant decrease of manufacturing time was achieved, picture 7. Compared to pure LMF manufacturing, the technology combination decreased the manufacturing time by more than 60 % from 13.8 hours down to 5.3 hours per blade.

During LMD manufacturing, the part temperature increases with each layer, influencing melt pool dimensions and process stability. In order to achieve a constant welding process, the laser power has to be controlled or cooling times between layers have to be applied. For high productivity multiple blades can be manufactured at the same time, using cooling times on one blade for continued material deposition on the next blade. For the shown turbine blade, a batch size of 18 blades allows for a continuous material deposition.



Picture 7: Manufacturing time

Advantages of the combined additive manufacturing with respect to the state of the art.

Compared to the state of the art, the following advantages are achieved by combined laser additive manufacturing:

Material flexibility: In the LMD process, material can be changed on the fly by adjusting the feed rate of different powder containers. The combined manufacturing method adds this feature with the geometric complexity of the powderbed process. This leads to new design options and allows components with graded material, while still maintaining complex geometrical features. Benefits are relevant in multiple industrial sectors, especially in the turbomachine industry.

Turbomachine efficiency: The new design of the turbine blade with complex inner lattice structures saves weight and improves heat exchange. This reduces the consumption of cooling air and therefore increases the efficiency of the turbomachine. Due to environmental awareness and the increasing scarcity of natural resources, the industrial demand for blades with advantageous designs is expected to rise.

Batch production: Blades with complex inner structures, which improve turbomachine efficiency, can only be produced with additive manufacturing processes. So far, low build-up rates in the powderbed prevented broad industrial use of these blades or similar parts. The described combined additive manufacturing reduces production time for the blade by 60 %, improving feasibility for batch production. This makes sure, that advantageous blade features are available for industrial application.

In order to best utilize the LMF-LMD combination in industrial applications, the following criteria should be assessed:

Part complexity: The combined laser additive manufacturing is most beneficial when the part consists of both complex and simple features. That way, the benefits of both technologies are utilized. For the turbine blade, part intricacy is represented in the lightweight and complex airfoil portion, while the simple fir-tree root section is comprised of relatively straightforward geometry.

Part interface geometry: The boundary between the two processes should provide enough stiffness to reduce welding distortion effects during LMD build-up. A flat surface, as represented in the platform of the blade, is advantageous for adjusting the LMD process.

Manufacturing materials: Benefits regarding materials can be gained whenever a multi-material design is advantageous. With LMD, a change of material can be done easily during the build-up process. One example is to deposit a hard material on the surface for wear protection, while the inner volume is created using a material with high toughness.

Production scale: The LMD's high deposition rates can be utilized most efficiently if multiple parts are processed the same time. That way, single parts can cool down while the welding head continues welding subsequent parts. For this blade, a production scale of 18 blades leads to a continuous deposition process. The process combination is therefore most beneficial in small-batch production.

The target groups of combined additive manufacturing are small and medium-sized enterprises, particularly service contractors of Rapid Tooling and Rapid Manufacturing, as well as suppliers of the automotive and turbomachinery industry and mechanical engineering in general.

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Combined Laser Additive Manufacturing for Complex Turbine Blades

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Abstract – Laser beam processes are increasingly used in the field of additive manufacturing. Prominent methods are either powderbed-based like Laser Metal Fusion (LMF), or utilizing a powder nozzle like Laser Metal Deposition (LMD). While LMF allows the manufacturing of complex structures, build rate, part volumes and material flexibility are limited. In contrast, LMD is able to operate with high deposition rates on existing parts, and materials can be changed easily during the process. However LMD shape complexity is limited. Utilizing their respective strengths, a combination of these two additive technologies has the potential to produce complex parts with high deposition rates and increased material flexibility. In this paper, combined manufacturing with additive technologies LMF and LMD is described. Its benefit for industry with emphasis on turbomachinery is shown. As reality test for the innovation, an industrial turbine blade is manufactured.

Keywords: additive manufacturing; laser metal fusion; laser metal deposition; turbine blade.