Lasers in Manufacturing Conference 2015

Additive Process Chain using Selective Laser Melting and Laser Metal Deposition

Benjamin Graf*,[a], Michael Schuch [b], Robert Kersting [a] , Andrey Gumenyuk [a,c], Michael Rethmeier[a,c]

[a] *Fraunhofer Institute for Production Systems and Design Technology IPK, Pascalstraße 8-9, 10587 Berlin, Germany*
[b] *Wehrwissenschaftliches Institut für Werk- und Betriebsstoffe (WIWeB), Institutsweg 1, 85435 Erding, Germany*
[c] *BAM - Bundesanstalt für Materialforschung und –prüfung, Unter den Eichen 87, 12205 Berlin, Germany*

Abstract

Selective Laser Melting (SLM) and Laser Metal Deposition (LMD) are prominent methods in the field of additive manufacturing technology. While the powder-bed based SLM allows the manufacturing of complex structures, build rate and part volumes are limited. In contrast, LMD is able to operate with high deposition rates on existing parts, however 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.

In this paper, a process chain consisting of additive technologies SLM and LMD is described. The experiments are conducted using the alloys Ti-6Al-4V and Inconel 718. A cylindrical test specimen is produced and the microstructure along the SLM-LMD zone is described. In addition, this process chain was tested in the manufacturing of a turbine blade. The feasibility of implementing this process chain for small batch production is discussed. The results are evaluated to show advantages and limitations of the SLM-LMD process chain. This paper is relevant for industrial or scientific users of additive manufacturing technologies, who are interested in the feasibility of a SLM-LMD process chain and its potential for increased deposition rates.

Keywords: Macro processing; additive manufacturing; laser metal deposition; Ti-6Al-4V; Inconel 718; process chain; deposition rate

---

* Corresponding author. Tel.: +49 30 39006374; fax: +49 30 39006391.
E-mail address: Benjamin.graf@ipk.fraunhofer.de

1. Motivation / State of the Art

Today, the trend to individualized products and decreasing time to market, leads to an industrial demand for flexible manufacturing technologies, Caffray and Wohlers, 2015. Additive manufacturing technologies offer high flexibility regarding complex design features and allow direct manufacturing from CAD-data without tooling, therefore saving time and costs, Levy et al., 2003. 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.

Despite their ability to manufacture highly complex parts, the industrial applications of powder-bed based technologies like Selective Laser Melting (SLM) 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 increase build-up rates for small and medium sized batch production. In recent years, different methods for this purpose have been discussed and developed. One method is to use higher laser power in order to melt multiple layers at the same time, Bremen et al., 2011. Another option are multi beam systems described by Buchbinder et al., 2011.

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 und Inconel 718 is described by Kool and Amsterdam, 2010. Material deposition for repair purposes and resulting mechanical properties are shown by Korinko et al., 2011 and Graf et al., 2012. In order to adjust process parameters for the additive manufacturing of a specific geometry, design of experiments can be used to determine the relation of process parameters and bead geometry, Graf et al., 2013.

Although SLM and LMD are increasingly covered in scientific research, a process chain of selective laser melting and laser metal deposition has rarely been described. The repair of tools made by selective laser sintering is described by Capello et al., 2005. As repair technology, laser cladding by wire is used. Multiple layers crack free and strongly bonded with the substrate could be deposited, although porosity was observed. Capello recommends a grinding process on the surface to reduce porosity in the clad.

A comparison of the two additive processes SLM 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 SLM while increasing build-up rates and material flexibility with LMD.

Table 1. Comparison of SLM and LMD

	Part dimensions	Structural complexity	Substrate	Material flexibility
Selective Laser Melting	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

2. Experimental

2.1. Additive technologies: Selective Laser Melting and Laser Metal Deposition

SLM is a common additive technology to process weldable materials. The technology 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. Figure 1(a) shows the SLM process.

The LMD process is shown in figure 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.

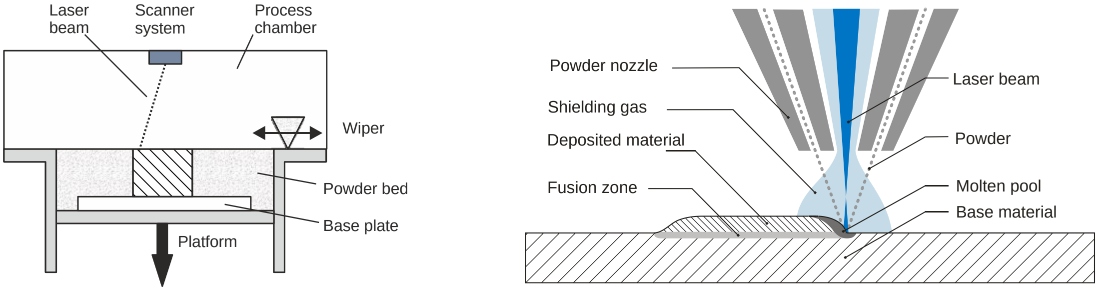

Fig. 1. (a) Selective laser melting process; (b) Laser metal deposition process

2.2. Microstructure in the vicinity of the SLM-LMD boundary

Cylindrical test specimen with a diameter of 18 mm are manufactured, first using SLM and then continuing material deposition on the SLM part with LMD. In the LMD part the following deposition strategy is applied: Along the circular contour, single weld beads are deposited. The inner volume is built with straight weld beads placed next to each other. The cladding direction is rotated each layer. In the SLM part, different process parameters are set for volume hatch and contour. The process parameters are shown in table 2.

Table 2. Process parameters for Ti-6Al-4V

	Laser power in W	Velocity in mm/min	Spot diameter in mm	Powder mass flow in g/min
LMD	1000	1000	1.0	3.75
SLM volume hatch	275	975	0.1	-
SLM contour	100	400	0.1	-

2.3. Turbine blade built by SLM-LMD process chain

A turbine blade with complex inner lightweight structures is manufactured applying the SLM-LMD process chain. The airfoil portion of the blade including its complex inner structures is built with SLM first. In the second step the fir-tree root of the blade is built up 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. The blade is built using 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 the process chain, the same blade is manufactured with SLM only.

Table 3. Process parameters for Inconel 718 blade manufacturing

	Laser power in W	Velocity in mm/min	Spot diameter in mm	Powder mass flow in g/min
LMD volume	1000	600	1.0	6.5
LMD high accuracy	800	800	1.0	6.5
SLM volume	250	700	0.1	-
SLM grid structure	150	350	0.1	-

3. Results

3.1. Microstructure in the vicinity of the SLM-LMD boundary

The microstructure in the SLM-LMD boundary zone is shown in figure 2. Different grain sizes are visible in SLM and LMD areas. Also the LMD deposition strategy can be recognized. The LMD contour is built with single weld beads on top of each other for good net shape. In the LMD inner volume, the cladding direction of two consecutive layers are perpendicular to each other. So in one layer weld beads are cut transversal (visible as half-circles), while in the next layer one weld bead is cut longitudinal. The heat affected zone in the SLM part (boundaries marked by the diffuse dark grey areas in the center of Fig.2) increases from left to right, showing that LMD deposition started on the left and continued to right. During the LMD process the part temperature increases which results in larger heat affected zones. The maximum heat affected zone is approximately 1.5 mm wide.

Overall, no cracks are visible at the boundary and in the adjacent microstructure. The SLM part contains single pores and small clusters of pores, especially in the contour area. The chosen LMD parameters lead to a good metallurgical bonding between single layers and to the SLM part.

Fig. 2. Cross-section in SLM-LMD boundary, Ti-6Al-4V

3.2. Turbine blade demonstration part

The turbine blade manufactured with the combined process chain is shown in figure 3. A significant decrease of manufacturing time was achieved. Compared to pure SLM manufacturing, the technology combination decreased the manufacturing time from 14 hours down to 5 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.

The fir-tree root is built near net shape. Further machining via CNC milling is required.

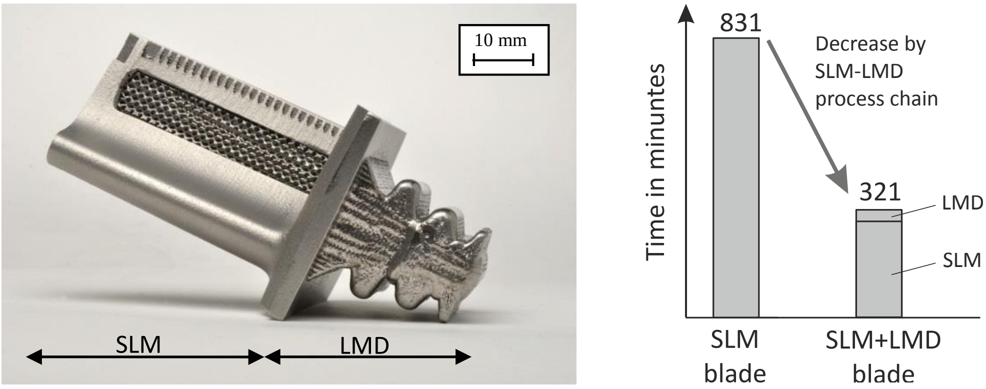

Fig. 3. (a) Turbine blade manufactured with combined SLM-LMD process chain, Inconel 718; (b) Manufacturing time for different parts

4. Discussion

4.1. Microstructure in SLM-LMD boundary

In order to use the SLM-LMD process chain for industrial production, the understanding of the resulting microstructure is important. The different grain sizes and porosity in the SLM and LMD part will result in different mechanical properties. Depending on the respective part requirements, a heat treatment to reach a homogenous microstructure can be recommended.

4.2. Turbine blade demonstration part

Complex inner lightweight structures in the blade increase functionality. Apart from saving weight while maintaining high stiffness, the inner structure leads to an increased surface to volume ratio, therefore improving heat exchange. In order to apply these advantages in industry, a manufacturing chain suited for batch production is necessary. In order to best utilize the SLM-LMD process chain, the following criteria should be assessed:

- **Part complexity**: The SLM-LMD process chain is most beneficial when the part has both complex and simple features. That way, the benefits of both technologies are utilized. For example, in 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**: Part geometry relates to the platform of the blade, which is used as the boundary between the two processes. The platform provides a flat and stiff surface for LMD build-up. The stiffness leads to a reduction of welding distortion effects.

- **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.

5. Summary and outlook

The difference of LMD and SLM microstructure regarding grain size and porosity is analyzed using Ti-6Al-4V. In the SLM built volume, the microstructure has higher porosity and smaller grain sizes compared to the LMD volume. The combined process chain of SLM and LMD leads to an increased deposition rate. This improves feasibility for small-batch production. The target groups of this manufacturing chain are small and medium-sized enterprises (SMEs), particularly service contractors of Rapid Tooling and Rapid Manufacturing, as well as suppliers of the automotive and turbomachinery industry and mechanical engineering in general.

In future work, heat treatment and its influence on mechanical properties for parts manufactured with the combined process chain will be analyzed. Parts made of Inconel 718 will be studied in a helicopter turbine test rig. This should highlight the suitability of additive processes for dynamically and thermally highly-stressed components and prove the applicability of the developed process chain.

References

Bremen, S., Buchbinder, D., Meiners, W., Wissenbach, K.: Mit Selective Laser Melting auf dem Weg zur Serienproduktion?, Laser Tech. J., vol 8, no. 6, pp. 271-278, 2011.

Buchbinder, D., Schleifenbaum, H., Heidrich, S., Meiners, W., Bültmann, J.: High Power Selective Laser Melting (HP SLM) of Aluminium Parts, Phys. Procedia, vol. 12, pp. 271-278, 2011.

Caffrey, T., Wohlers, T.: Wohlers Report 2015: Additive Manufacturing and 3D Printing State of the Industry.

Capello, E., Colombo, D., Previtali, B.: Repairing of sintered tool using laser cladding by wire, J. Mater. Process. Technol., vol. 164-165, pp. 990-1000, 2005.

Graf, B., Ammer, S., Gumenyuk, A., Rethmeier, M.: Design of Experiments for Laser Metal Deposition in Maintenance, Repair and Overhaul Applications, Procedia CIRP, vol. 11, pp. 245-248, 2013.

Graf, B., Gumenyuk, A., Rethmeier, M.: Laser Metal Deposition as Repair Technology for Stainless Steel and Titanium Alloys, Phys. Procedia, vol. 39, pp. 376-381, 2012.

Kool, G., Amsterdam, E.: Laser additive manufacturing of titan and Inconel, The Future of Gas Turbine Technology, 5th International Gas Turbine Conference, Brussels, Belgium, 2010.

Korinko, P. S., Adams, T.M., Malene, S.H., Gill, D., Smugeresky, J.: Engineered net shaping for repair and hydrogen compatibility, Welding Journal, vol. 90, pp. 171-181, 2011.

Levy, G. N., Schindel, R., Kruth, J. P.: Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives, CIRP Ann. – Manuf. Technol., vol. 52, no. 2, pp. 589-609, 2003.