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Laser metal deposition of Ti-6Al-4V structures: new building strategy for a decreased shape deviation and its influence on the microstructure and mechanical properties

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Abstract

The laser metal deposition (LMD) process is used to increase the productivity rate in the field of laser additive manufacturing. Large structural Ti-6Al-4V components can be manufactured resource efficiently with this approach. In contrast, conventional manufacturing processes machine up to 95% from the bulk material to produce parts for the aerospace industry, as described by Peters et al., 2003.
Compared to the powder bed based additive manufacturing the LMD process generates a local material deposition by feeding the powder directly to the substrate. On top of the surface, the laser beam will liquefy the additional material. Consequently a single track is deposited, which can be extended to a surface or 3D-structures.
To qualify the LMD process for an economic industrial use, it is necessary to understand the physical phenomena during the building process. Especially for high wall structures, the thermal boundaries vary with the building height and therefore the process lacks in reproducibility and quality-. In this paper, a new approach of adapted process parameters to the thermal conditions during the building process is presented. The laser power and processing speed vary for every layer until a stable building rate is achieved. The aim is to narrow the geometric tolerances of the additive manufactured structures. In addition, the influence of the building strategy on the resulting microstructure is determined.

Keywords: laser metal deposition ; additive manufacturing ; titanium ; building strategy ; microstructure.

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1. Introduction

The applications for additive manufacturing (AM) are continuously increasing due to a deeper understanding of the physical operating principles of the technologies used for AM. Because of the layer-wise part building, complex shaped three-dimensional structures beyond the limits of conventional machining are now feasible. Therefore, the AM market is mainly driven by lightweight components made of high-performance materials like titanium. The understanding of the physical operating principles is still limited and a reliable AM process chain is the central focus of many R&D departments.

The advantage of the laser metal deposition (LMD) process in contrast to the powder bed based process is that locally necessary material is directly deposited on the wrought material. Design guidelines have been published for powder bed based laser AM of titanium by Kranz et al., 2015. These improved the reliability of the process and therefore increased its profitability. These guidelines are not fully applicable for the LMD process due to the different thermal process boundaries. For powder bed based systems the first 30 to 80 layers are usually just support structures between the component and building platform. For the further part building the high heat transfer rate into the building platform is therefore negligible. The thermal conditions are nearly constant throughout the building height with a surrounding powder bed for every layer. In contrast, the LMD process feeds the additional material directly to the substrate. Furthermore, the heat transfer from the deposited track to the environment changes significantly with an increasing distance to the baseplate. While the solid to solid heat transfer of the first layers is to the comparatively large baseplate, at further distances the conductive heat transfer is limited to the area of the horizontal cross section of the manufactured wall.

As a result, anisotropic material properties along the building height were observed in the work of Brandl et al., 2010 and Paydas et al., 2015. In addition, the geometrical accuracy of the built part is reduced with increasing building height. Moeller et al., 2016-2, showed that layer-wise adapted laser power is a promising approach to reduce this shape deviation for high wall structures.

A predictive and reliable part-geometry is the key to reduce the post-process machining effort. If the shape deviation decreases to a minimum without random wall thickness defects, the milling of functional surfaces can be reduced. The subtractive post-processing is a significant cost factor due the challenges when machining titanium with its low thermal conductivity and high hardness. For that reason, the presented building strategy with adapted process parameters is a promising approach to increase the implementation of the LMD process in industrial AM chains.

2. Experimental setup

The manufacturing of the high wall structures is executed with a Trumpf TruDisk 6001 cw disk laser with a wavelength of 1030 nm. The spherical powder material is sieved to a fraction 63 to 100 µm and subsequently transported with a rotational table feeder to the process. The processing head consists of three coaxial outlets for the powder. Argon is used to shield the process against oxygen supplied in a process chamber and helium is used to transport the powder from the feeding unit to the processing head.

The determination of shape deviations was evaluated by measuring the thickness deviation through a tactile measurement executed with a coordinate measuring machine (Wenzel LH87) with an accuracy of (1.8 + L /350) µm. All tactile measurements were executed as shown in the figure 5. In order to measure the thickness deviation 200 points were set along the building height in the middle of each side and 100 points were used to measure the height. For the temperature measurement, thermocouples (TC) of type K were used. Boron nitride was used to ensure a better heat transfer from the substrate to the TC.

Radiographic inspection was used for assessing the quality of the wall structures in terms of porosity, cracking and thickness deviations. For the metallographic analysis, cross-sections from the 70 mm long walls were taken from the middle, grinded, polished and etched with Krolls solution. The microstructure was analysed with an optical microscope.

3. Building strategy

The general building strategy to manufacture walls is to alternate the deposition direction. Start and end points switch with every layer and the position in z-direction increases by a defined offset after each deposition track while the laser is turned off. The laser power is increasing and decreasing at the start respectively end of every track with a ramp. The wall thickness is defined by the width of a single track.

In order to have a more efficient part production, the approach for laser metal deposition is to use wrought material and locally deposit necessary material. Thus, the heat transfer in form of conduction from the first layers into the solid material is very high. Cooling rates are observed to be even larger than in water quenching as described by Luetjering 1998. With increasing building height – equal to the generation of multiple layers – the heat transfer mechanism change significantly. Since the distance to the building platform increases and the volume of the deposited wall is small compared to the wrought material, the heat conduction decreases. The heat convection and radiation increase with the building height, due to a larger surface and become the dominant heat transfer mechanism for high wall structures.

To quantify those assumptions, temperature measurement with thermocouples on the baseplate were conducted. Fig. 1 shows a fast increase of the temperature on the baseplates surface for the first deposited layers. After a certain time it was observed that the temperature on the baseplate is decreasing while the process continues. This can be explained by the fact that with increasing building height the heat conduction into the substrate, where the TCs were mounted, was reduced. This finally resulted in a heat accumulation and thus in a reannealing of the last deposited layers.

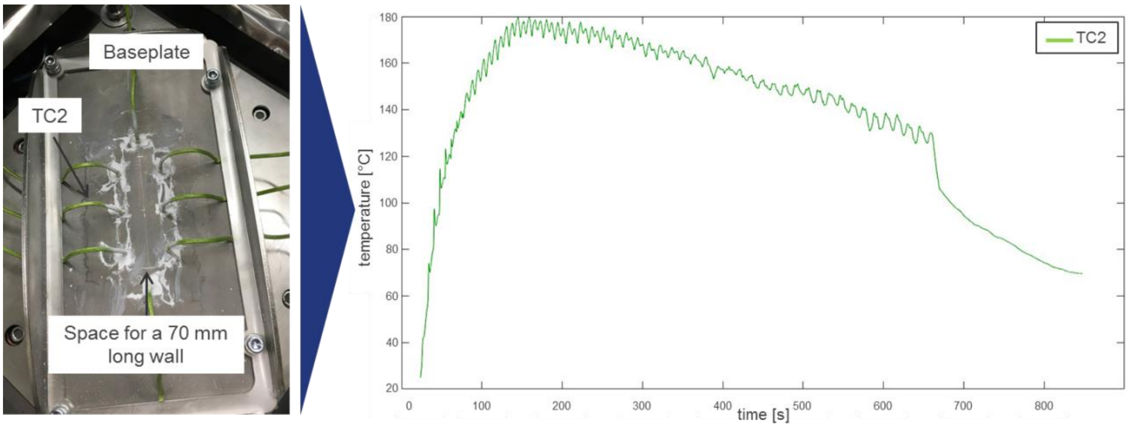

Fig. 1. Experimental setup for the temperature measurement of the baseplate during the LMD process and the resulting graph for 90 layers.

Constant process parameters as well as sensor based process monitoring systems like temperature measurement with a pyrometer neglect changing heat transfer conditions. Sensors that measure a current state of the system and adapt for example the laser power are just reacting to an unstable process condition, as demonstrated by Koehler et al., 2013. The new approach of a priori process parameter planning is thus a preferable alternative or addition to sensor based process monitoring.

The following approach of varying the energy per unit length by different functions along the number of layers is based on the optimized laser power variation from Moeller et al., 2016-2. The corresponding graphs are shown in Fig. 2.

While the variation from Moeller et al., 2016-2, consists of three different sections in the graph, the aim for the new building strategy was to have a continuously differentiable function to minimize the change of parameters within two layers. The graphs in Fig. 2 show that the energy input is decreasing with the building height and result in a constant value after a certain amount of layers.

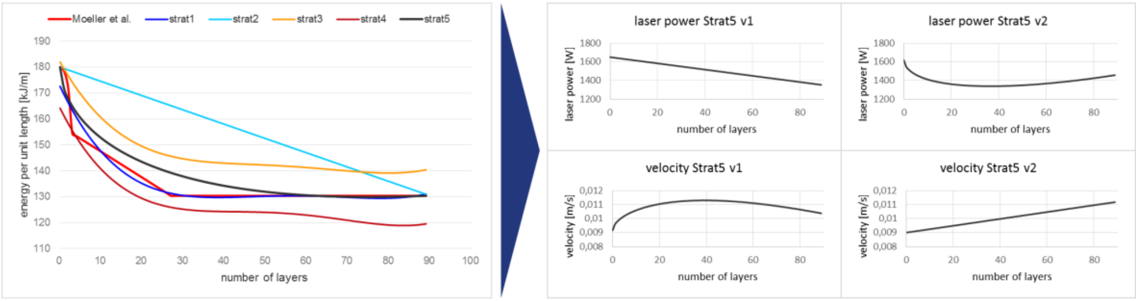

Fig. 2. Examined functions for the energy per unit length based on the optimized result from Moeller et al. (left) and resulting functions for the laser power and velocity for the energy per unit length of 'Strat5'(right).

Two walls were built for every function displayed in Fig. 2. In order to change both process parameters, laser power and velocity, at the same time for each layer, one parameter was decreasing linearly within a defined range of the optimized parameter for a single track while the other parameter was adapted to the energy per unit length after equation:

$$E_{length} = \frac{P_L}{v_L} \tag{1}$$

The resulting functions for the laser power and velocity are exemplary shown for strategy 'Strat5' in Fig. 2 on the right.

4. Shape deviation

In order to grant a better overview, Fig. 3 summarizes the evolution of how the adapted process parameters were developed. It also shows which quantities were evaluated and presented in the following of this paper.

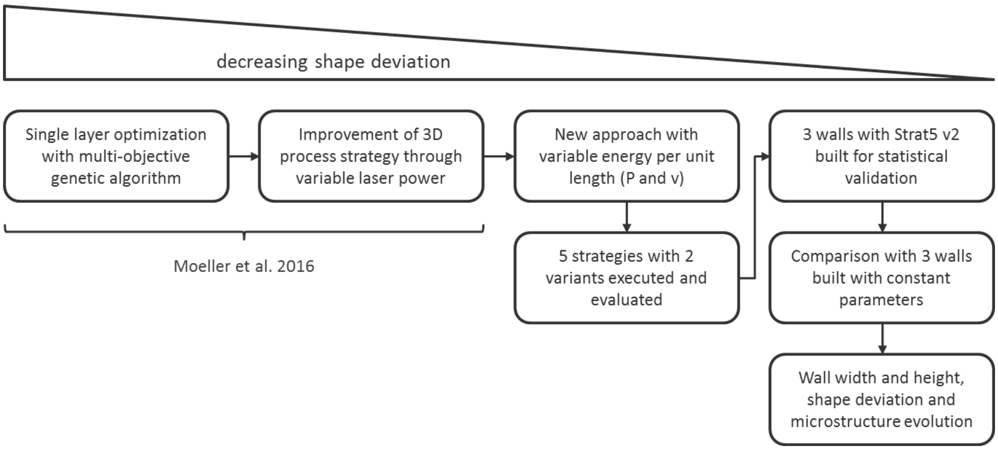

Fig. 3. Evolution of the adapted process parameter development for building high wall structures.

The results from the tactile measurements for the five different building strategies are shown in Fig. 4. It can be seen that the manufactured wall with constant process parameters has higher standard deviation in the resulting wall thickness. In addition, shape defects and a rough surface can be observed with an increasing building height when using constant parameters. In comparison, with the adaption of process parameters, a steady and more regular layer-wise metal deposition could be achieved.

Building strategy 'Strat1 v2' results in the lowest standard deviation of the wall width. However, the best overall result could be achieved with strategy 'Srat5 v2' because of a more steady building height, better powder efficiency and a greater wall width. Therefore, building strategy 'Strat5 v2' was used for the further investigations.

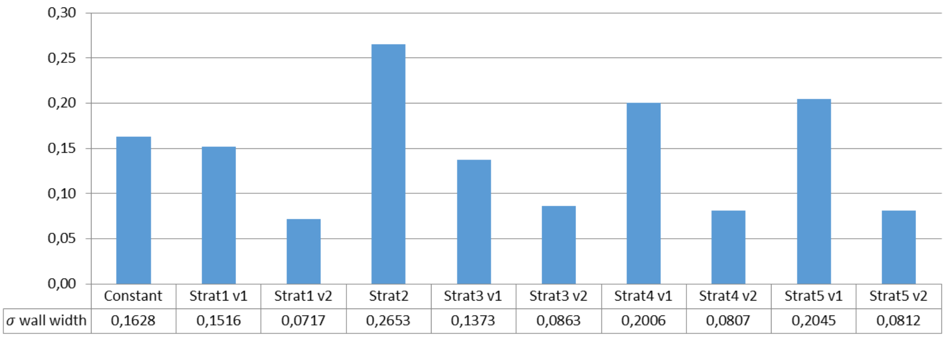

Fig. 4. Results for the standard deviation of the wall width for building strategies v1 to v5 (adapted process parameters) compared to building a wall with constant parameters

For statistically ensuring these results, three walls with adapted parameters of ‘Strat5 v2’ (in the following referred as ‘1X’, ‘2X’ and ‘3X’) and three walls with constant parameters (in the following referred as ‘1’, ‘2’ and ‘3’) were built. The outcome of these experiments was compared to each other and is shown in Fig. 5.

The wall marked with a red cross was built with different parameters and is therefore not considered in the evaluation. In the same row, three walls with constant parameters were built. The row in the foreground of the picture shows three walls built with adapted parameters.

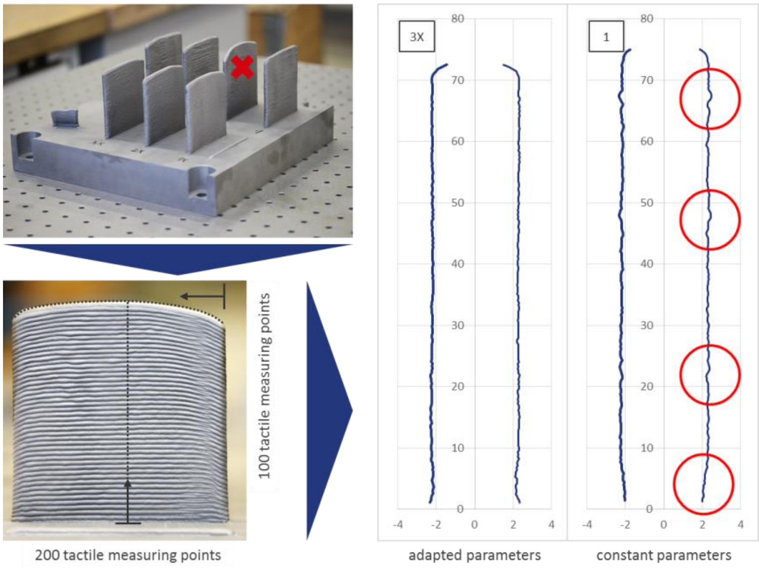

Fig. 5. Ti-6Al-4V building platform with LMD manufactured walls and measuring position for the tactile evaluation (left) and resulting cross sections exemplary for wall ‘1’ and ‘3X’ (right).

The graphs on the right in Fig. 5 represent the measured cross section of wall ‘3X’ and ‘1’. As highlighted, inhomogeneity can be observed along the height for wall ‘1’ with constant parameters. In addition, the first couple layers are significantly smaller in diameter than the following ones. The utilizable wall thickness after machining is defined by the smallest wall thickness. Therefore, welding with constant parameters result in a higher post-processing effort because all the additional material has to be removed. In comparison, the cross section of wall ‘3X’ shows a steady building process with a constant wall thickness along the building height.

Fig. 6 shows an optical surface comparison of wall ‘3X’ and ‘1’ and the mean results of wall height, width and standard deviation of the wall width. The error bars represent the minimum and maximum values from the three manufactured walls. It can be seen that the use of adapted parameters resulted in an averaged lower building height of 4.2%. The mean wall width stays nearly the same. However the standard deviation of the wall width is reduced by 30.2%.

5. Radiographic inspection

For a thoroughly evaluation of the manufactured walls, a radiographic inspection was conducted. Fig. 7 shows the radiographs of a wall with adapted and constant process parameters.

The walls are almost defect-free. Only isolated micro-pores were detected. No cracks were found throughout the wall structures. Furthermore, the brightness indicates differences in wall thickness, while the darker areas represent thinner and brighter areas represent thicker material accumulations. Hence, the optimized wall has a more homogenous wall thickness throughout the building height than the reference wall.

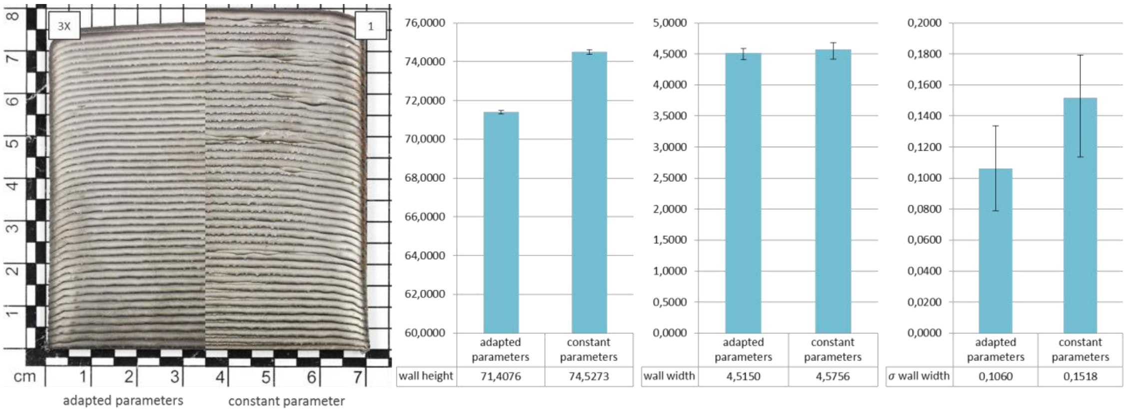

Fig. 6. Comparison of the walls manufactured with constant and adapted parameters.

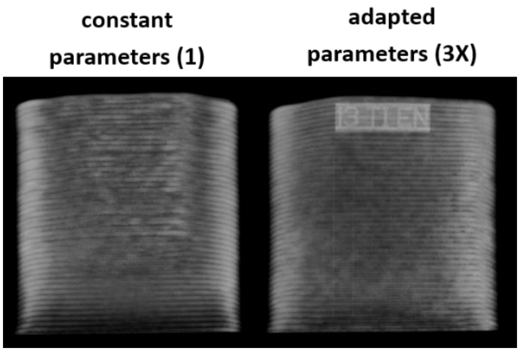

Fig. 7. Radiographs of the wall structure with adapted parameters (left) and constant parameters (right).

The necking at the bottom of the wall due the high heat transfer into the substrate can be observed for both strategies. However, it is less for the optimized wall structure manufactured with adapted parameters in comparison to the wall structure manufactured with constant parameters.

6. Microstructural characteristics

The microstructure of the LMD manufactured Ti-6Al-4V walls three regions along the building height could be differentiated. This graded microstructure is shown in Fig. 8.

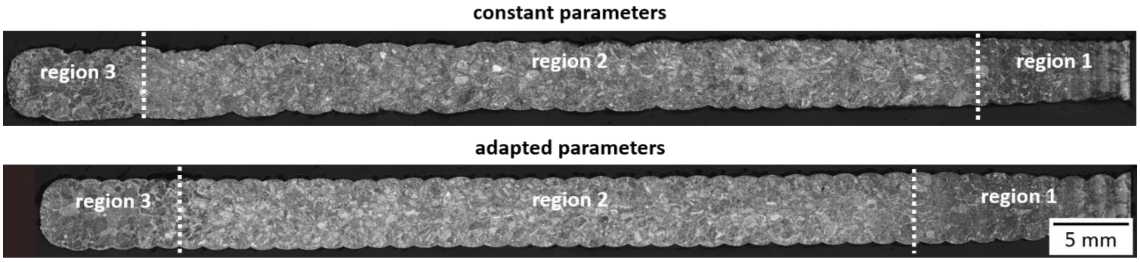

Fig. 8. Cross section in the middle of the LMD manufactured wall

In region 1 at the bottom of the wall structure, the cooling rates are assumed to be high due to the heat transfer into the solid substrate. The microstructure consists of α' martensite. Therefore, the cooling rate for these first layers has to be in the range of 20-410 K/s as described by Ahmed et al., 1998. Moreover, the individual deposition layers are clearly visible. In region 2 the layer interfaces disappear. This region is characterized by a coarse lamellar microstructure due to slower cooling rates. Compared to region 1 the cooling rate must have been decreased to 20 K/s.

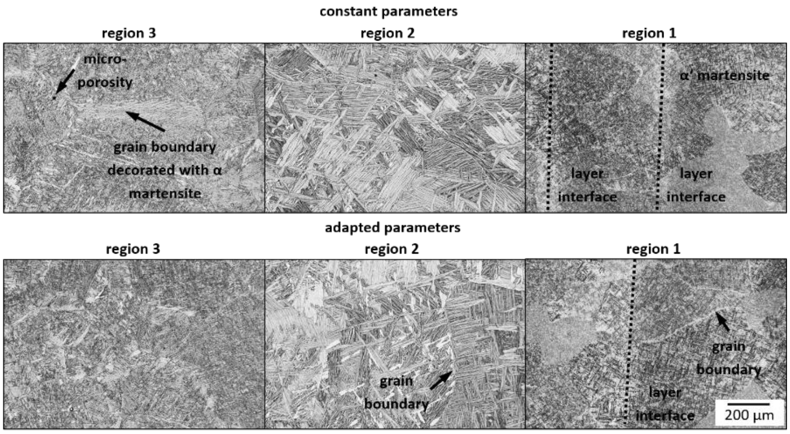

Fig. 9. Three different microstructures that occur during the LMD of Ti-6Al-4V

The change in microstructure from region 1 to region 2 can be seen after approximately 12 layers for the constant parameters and 16 layers for the adapted LMD parameters. This correlates with the visual analyses of the process monitoring. During LMD the material was deposited layer-wise and thus the first layers have a certain time to cool down below a temperature where no annealing is visible. From that point on, a constant amount of layers are annealing throughout the building process. The impact on the microstructure can be seen in region 3. This is approximately the amount of layers that anneal during the building process. Once the building process is finished, no further heat input takes place and a reannealing of the last layers occurs. This results in a fine lamellar microstructure, while the grain boundaries are decorated with martensite.

7. Conclusions

Referring to the results obtained in this study the following conclusion can be drawn:

- It was possible to improve the overall surface appearance of the wall structures by using adapted LMD process parameters.
- There was no significant porosity and no cracks were found in a 90 layers and 70 mm long deposited Ti-6Al-4V wall.
- A non-linear change of the processing speed during LMD results in an unstable building process and therefore an increased shape deviation.
- The adapted process parameters result in a bigger α’-martensite region at the bottom of a deposited wall compared to welding with constant parameters.

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