Quality Management of Laser Cladding Processes for Additive Manufacturing by new Methods of Visualization and Evaluation of Thermographic Data

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Abstract

Additive manufacturing by laser cladding is a promising tool for rapid prototyping, building of bionic structures and replacement part production. To ensure a constant quality of manufactured components and to shorten the development process between CAD model and suitable produced components a quality management system is inevitable. Therefore, a system has been developed to evaluate the cladding process by means of thermographic measurements. Melt pool temperature measurements by a thermal imaging camera has been processed to a 3-dimensional temperature map of the manufactured component, like a tomographic image, to easily reveal weak spots in the process and the component itself. The quality management system was tested and evaluated on several laser-cladding processes with various failures.

1. Introduction

For years, laser cladding is a common technique for non-porous and crack-free surface coating and finishing preventing components from corrosion and wear as well as the repair of worn machine parts. Since emerge and great success of the topics rapid prototyping and 3D printing of polymers the development of laser cladding moves in the direction of additive manufacturing. This enables a rapid prototyping of metal parts and the resource-efficient production of replacement parts without milling and cutting. Further advantages are the opportunity of producing very complex structures such as bionic designs to increase the stability of components by reducing the weight at the same time as well as the integration of material gradients [1].

For building a readily usable machine part from a CAD model in industry quality and with high reproducibility, it needs a high understanding of the process and prolonged component studies for every new component part and material [2]. The effort of this development process strongly increases with growing complexity of manufactured parts. Therefore, an extensive process monitoring is inevitable. The process monitoring generates a huge amount of data, which must be analyzed by a quality management system, which evaluates and visualizes for the machine operator to decrease the length of component studies and ensure a steady quality. Especially these component studies can involve destructive, time-consuming, and cost-intensive metallographic investigations or non-destructive but still cost-intensive and time-consuming x-ray analysis such as computer tomography [3].

2. Laser cladding as additive manufacturing

Powder fed laser cladding is a technique where a focused laser beam heats up a substrate to generate a melt pool. Simultaneously a focused stream of inert gas carries metal powder into the melt pool. By moving the coaxial powder nozzle, including the laser beam, the system can build up 3D metal structures layer by layer.
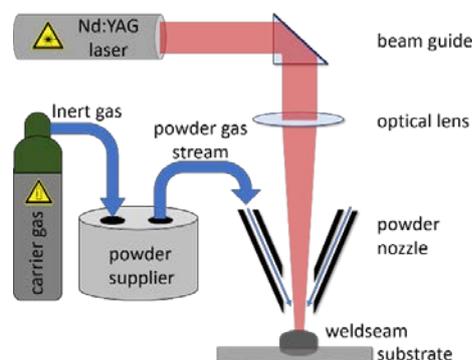
Figure 1: Schematic of the laser cladding principle with coaxial powder nozzle

A schematic of a powder feed laser cladding system is shown in Figure 1. In comparison to well-established powder bed systems such as selective laser melting (SLM) systems, the laser cladding systems are able to build up larger volumes [3] and the wastage of the cost-intensive metal powder is significantly lower.

3. Melt pool temperature measurement

The measurement of the melt pool temperature was performed by a PI 05M thermal imaging camera developed by the company Optris GmbH. This is a camera specially designed for temperature measurements of molten metals. Due to its spectral range of 500-540 nm it can handle the low emissivity of reflective metal surfaces and shows a temperature sensitivity at 900 – 2000°C and a resolution of 382 x 288 pixel at a frame rate of 80 Hz.
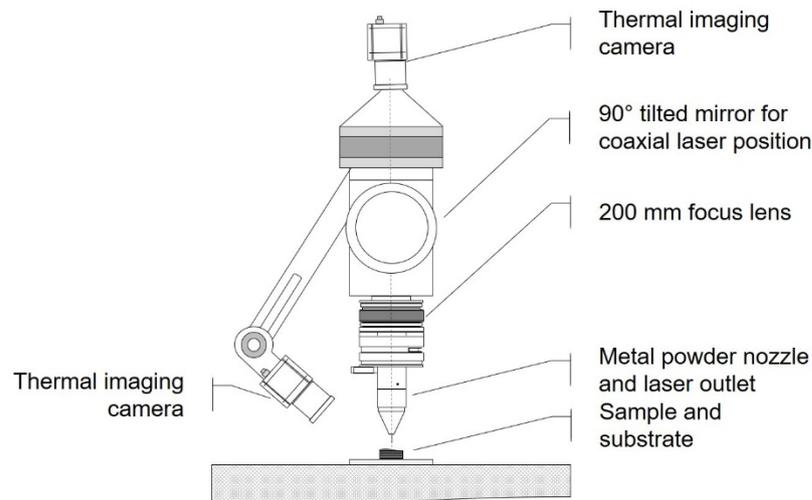
Figure 2: Powder nozzle with mounted thermal imaging cameras

Figure 2 shows the arrangement of the cameras at the laser cladding system. The first camera was mounted at an angle of 45°. This has the advantage of a wider view overall manufactured component and a more detailed image of the melt pool due to its small distance to it. The second camera is mounted coaxially to the optical path on the top. Due to the so far not yet implemented optic the melt pool is not resolved in a very high resolution even if the lens causes a magnification and the components of the optical path such as a mirror/beam guide and the lens are causing transmission losses which need to be factored in by the camera software. But the great advantage of the coaxial mounting is an always free view to the complete melt pool and no dependency on the direction of powder nozzle moving.
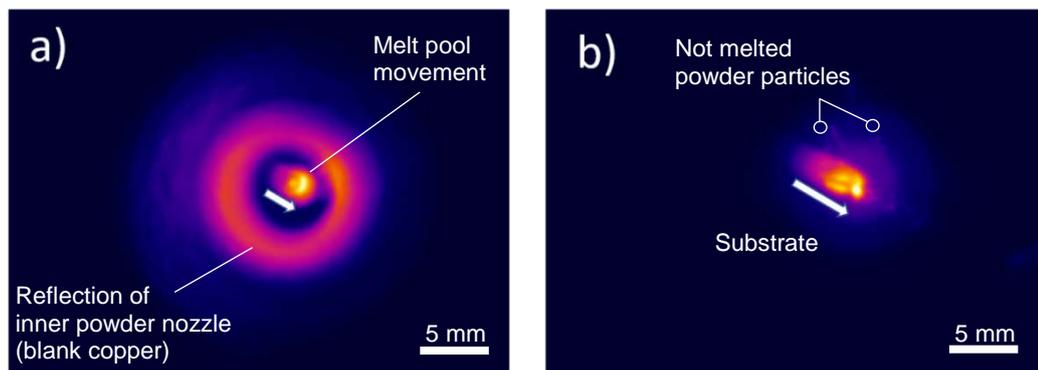
Figure 3: The view on the melt pool by the thermal imaging camera coaxially from the top a)
and from the side at an angle of 45° b). The arrows are indicating the welding direction.

In Figure 3 are shown twice-zoomed images of the melt pool recorded by the different mounted thermal imaging cameras. The white arrows are indicating the current welding direction. Figure 3 a) shows the melt pool from the coaxially mounted camera. The halo around the melt pool is its reflection at the inside of the powder nozzle. Figure 3 b) shows the side view of the melt pool. The magnifying effect of the lens can be seen here very well since the melt pools are imaged at almost the same size despite the different camera distances from the melt pool. The disadvantage of the side view is that the melt pool can be tilted especially at the edges of structures. If the tilt is relatively strong and to the opposite direction of the camera a significant part of the melt pool can be hidden from the camera.

4.   Quality management for laser cladding processes

The focus of research with the attempt to improve the quality, reproducibility and precision of additive manufacturing by laser cladding currently relies on the integration of laser power or scanning velocity closed-loop control systems. These systems mostly use an input of melt pool temperature data obtained by sensors such as pyrometers, clad height or melt pool width data with the goal to keep constant cladding conditions and quality across the whole laser cladding process [4, 5, 6]. Many of these attempts showing increased component quality but there is still much space for improvements.

Another very promising and powerful in-process controlling system is the so called optical tomography [7]. This method is based on the time exposure by a CMOS camera during the build of every single layer. The result is a stack of images which is merged to a 3D model by a tomography software. With the aid of this model and the images of the single layers it is capable to detect defects and weak spots in the built component and the build process itself. This tool has proved its abilities and is even used to build components for aerospace applications. Unfortunately, it was never tested on laser cladding because it is presumably exclusively applicable on selective laser melting systems since it needs an open view on the whole component. Due to the moving powder nozzle in laser cladding processes this requirement is not fulfilled.

4.1. 3D-Modeling of melt pool temperatures

Therefore, a new tool specifically made for laser cladding systems needs to be developed. While the optical tomography builds 3D models from 2D data, the system for laser cladding builds 3D models from 1D data. These 1D data are given by the melt pool temperature measurements. This means every temperature point is represented by a voxel, a three-dimensional pixel, in the resulting 3D model. The idea here is to use the so-called G-Code, the programming code that includes all parameters and the cladding strategy the machine needs to perform a cladding job, as the 3D framework for the one-dimensional temperature data.
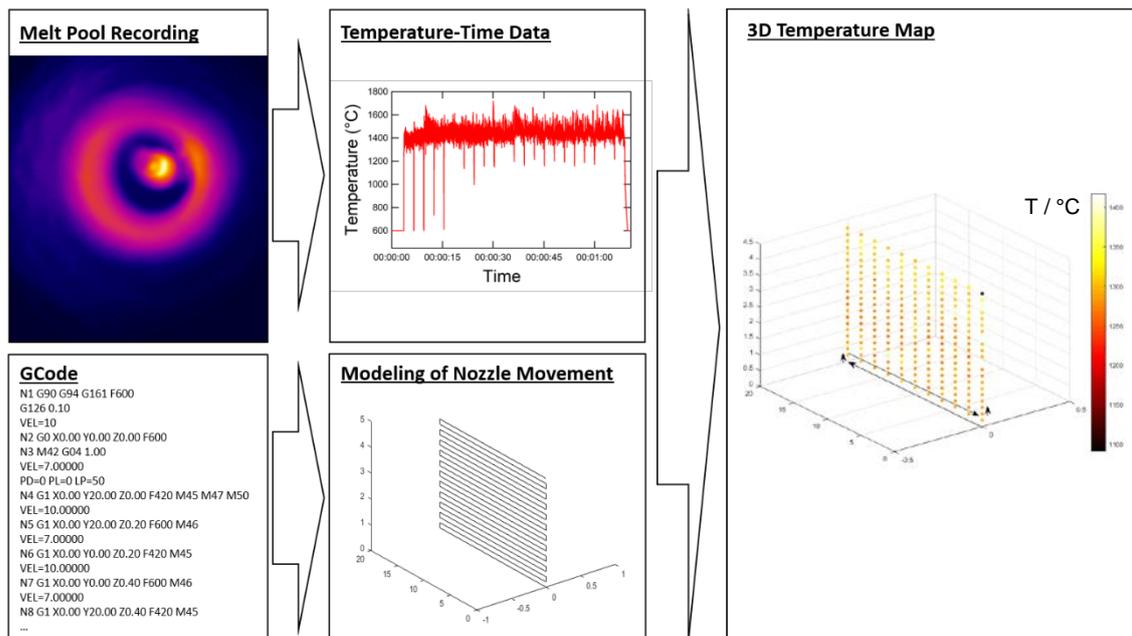
Figure 4: Principle of collecting and merging process and temperature data to a 3D temperature map of the built component on the example of a small wall

In Figure 4 the methodology of reconstructing the thermal measured data by coaxial mounted infrared camera and the machine coding was combined to test the analytic approach. The adaption of G-Code files has to be handled first with the main interesting parameters: absolute coordinate xyz, velocity of nozzle movement ('VEL') and the de-selection of laser-off times ('M46'). To analyze the logged temperature data versus time, the clustering of different temperature segments will be helpful to allocate defined geometrical segments.

The temperature values delivers a more or less precise data set to show at which time the laser was turn off, to move to another position. For this study, the movement of the powder nozzle during laser off times is neglect able. Later on, lateral mounted infrared cameras can measure thermal heat flow to the substrate at laser off times and analyse the continuous powder melt. In the first approach, the measured temperature points show an increasing temperature distribution due to assembling a simple wall with up to 22 layers in alternating directions. The illustrating image of nozzle movement contains thereby also the movement in z-direction. In combination of both segments, the resulting temperature map of the idealized wall are used to evaluate hot melt spots due to laser power increase or cold areas induced by too much metal powder.

To go further with typical assembled test structures, a coupled pyramid object in a cube figured out to observe local temperature points in a three-dimensional form. For assembly was done by laser cladding machine by the following parameters (Table 1).

Table 1: Parameters of laser cladding process and the dimensions of the test structures

Laser cladding parameters			Dimensions of geometrical test structure	
Laser power [W]	315 (70 %)		Cube (out) [mm³]	20 x 20 x 20
Laser spot size [mm]	1.2		Pyramid (in) [mm³]	14.14 x 14.14 x 15
Velocity nozzle [mm/s]	7		Layers	55 (cube), 41 (pyramid)
Powder speed [U/min]	1		Material	Stainless steel, 316L
Inert gas add on	Nitrogen		Substrate	Steel (thickness ~ 4 mm)

The read-out of the modeled G-Code file represents the reversal points from every single code line (Figure 5a). A fully assembled image of the cube including steel substrate represents Figure 5b. The complete duration of the construction process has taken more than two hours without any machine failure. After cross sectioning of the cube assembly (Figure 5c) the inner pyramid structure show, that during processing the top of the pyramid some of the melt pool material goes directly to the base plate. A typical surveillance during heat concentration on small areas. The temperature was measured with the infrared camera coaxial through the powder nozzle during this process.
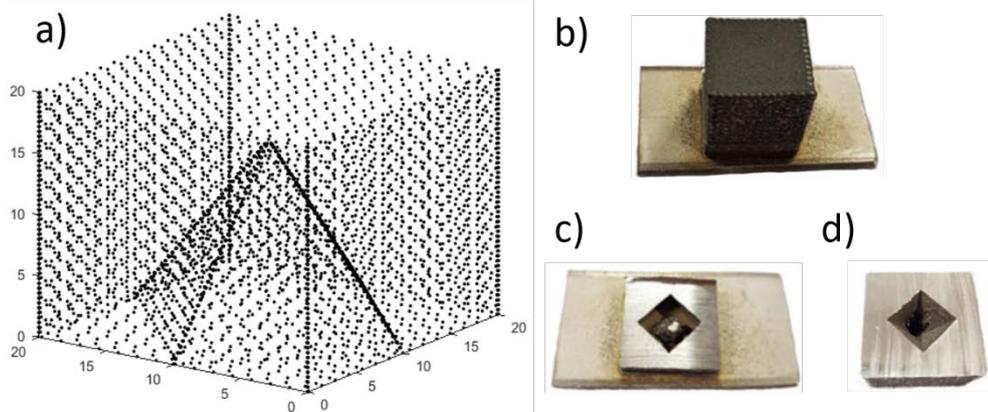
Figure 5: Three-dimensional point model of the test structure made by G-Code a), a photo of the assembled test structure (powder: stainless steel) b) and the sliced structure with a view on the pyramid shaped notch c) and d)

The infrared camera focuses a planar view to the melt of the metal powder. Therefore, a pixel wise analytic recording of the melt pool was set up to avoid local disturbances by non-melted powder particles or nearby reflections. An 81 x 81-pixel matrix for temperature delivers continuous data of melt pool movement. For the first estimations, the arithmetic mean value of the pixel array was used. Later on, histogram distributions can show the temperature profile more precisely.
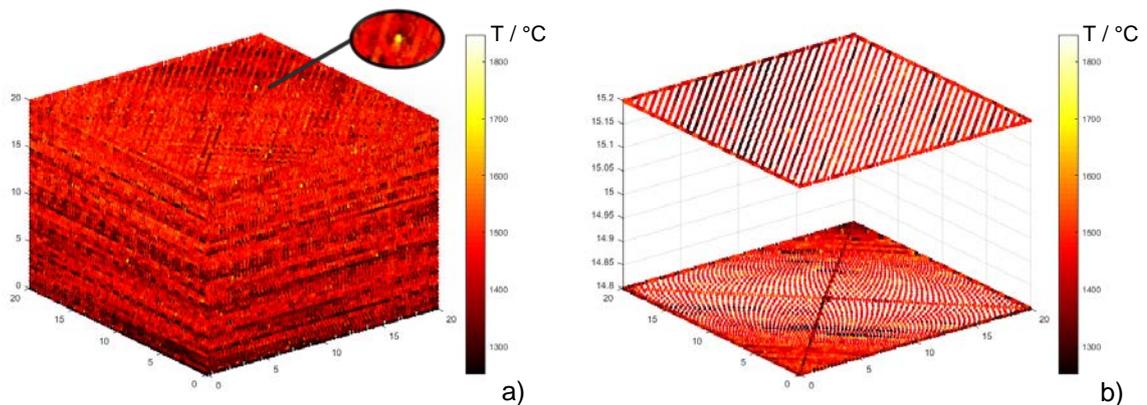
Figure 6: Measured temperature map combined with the extended three-dimensional coordinates of the G-Code file a), a detailed view into layer structure during the transition phase of the pyramid top level and the cube b)

Figure 6a show the generated analytic result of temperature data with the extended data values of the machine produced G-Code file. The dimensions are idealized and the temperature values delivers the expected temperature range – bottom around 1300 °C, top-level 1400 to 1500 °C. In some single pixel the mean temperature rises up to 1800 °C (small figure) which could be understand to local concentrated higher power density of the laser or as measurement failure

induced by direct reflection of particles. In Figure 6b the intersection of top level pyramide (layer 41) and the ongoing cube assembly indicates a homogenious temperature during process.

5. Conclusion

The first analyzed results show the expected outcome of the thermal imaging data, but with the advantage should be to observe local three-dimensional hot and cold spots, temperature increases in every single layer or visualisation of sliced geometrical assemblies. The improvement of synchronised local coordinate data values and the higher time and temperature resolution will take into account to manage the data easier and get a reference to following assembled test series in different parameter set. With a test series according to change laser power and nozzle velocity a detailed test matrix will help to find out which parameter set works probably well and should be taken as reference for machine learning. In addition, cross sections and metal microstructure analysis can be helpful to validate the contactless measured data. Meanwhile, in future work the focus of the following innovative steps push additive manufacturing to the next level:

- High data processing including online position monitoring and comparison between analytical G-Code

- Thermal in-situ observation with pyrometer and infrared camera during long-term cladding processes

- Self-learning machine coding due to parameter changes, e.g. laser power, velocity and/or powder material

In this stage of study the results present the outcome and the benefit of these methology and their implementation to laser cladding systems. Ongoing measurements and analysis of more complex test structure (diagonal walls, thin sticks, and inverse cone) will be figured out with this method in different parameter sets of the laser cladding system and will be published within next publications.

6. Acknowledgements

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