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Feedback control of Layerwise Laser Melting using optical sensors

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Abstract

Layerwise Laser Melting (LLM) is a layerwise production technique enabling the production of complex metallic parts. Thin powder layers are molten according to a predefined scan pattern by means of a laser source. Nowadays constant process parameters are used throughout the build, leading for some geometries to an overly thick feature size or overheating at downfacing surfaces. In this paper a monitoring and control system is presented which enables monitoring the melt pool continously at high speed throughout the building process. The signals from the sensors can be incorporated in a real-time control loop, in this way enabling feedback control of the process parameters. In this paper the experimental set-up will be first shown. Next the dynamic relation between the melt pool and the process parameters is identified. Finally the proof of concept for feedback control is demonstrated with experimental results.

Keywords: *Monitoring; feedback control; layerwise laser melting; optical sensors*

1. Introduction

Layerwise Laser Melting (LLM) is a layerwise production technique enabling the production of complex metallic parts. In this process thin layers of metal powder are deposited by means of a powder coating system. Next the powder is molten at selected places according to a predefined scanning path by means of a laser source [1]. The laser source is deflected by two galvano mirrors towards the building platform, according to a predefined scan pattern. The process chamber is filled with an inert gas, typically nitrogen gas for processing of steels and argon for processing of reactive materials as e.g. titanium or aluminium. Processing in ambient air leads to formation of brittle oxides in the material. The LLM process has a large potential: almost infinite geometric freedom, no need to design/make dedicated tools for production, flexibility for customised individual parts. Since material properties of LLM parts are nowadays comparable to the properties of the corresponding bulk material, applications of the process can be found in quite diverse domains, like the medical sector, e.g. dentistry [2, 3], in tool making industries for manufacturing of tools [4–7], the general manufacturing industry (machine construction, automotive, etc.) while the potential in production of lightweight structures [8] is investigated for aerospace applications.

For every material processed on a certain LLM apparatus the process parameters, i.e. laser power, scan velocity, layer thickness and hatch spacing (i.e. the spacing between subsequent vectors) need to be optimised. During the build process these process parameters are mostly kept constant. However, the use of static process parameters not

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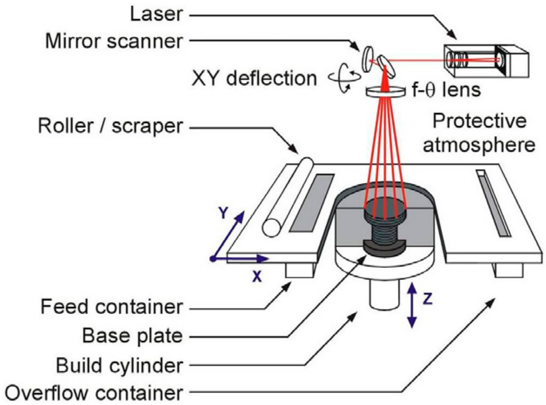

Fig. 1. Schematic overview of typical LLM machine

always leads to good results: e.g. thin features are overly thick or overheating can occur at places where there is hardly no solid material in the neighbourhoud to remove the heat from the melt pool. Recent research on LLM of Ti6Al4V showed that small changes in process conditions can lead to large differences in the microstructure [9].

To overcome the problem of variations in melt pool due to influences of local geometry, two approaches can be distinguished. In the first approach a priori knowledge on the part is used, combined with experimental data to adapt the process parameters locally in function of the geometry. This approach can be considered as 'feedforward control'. However, a large experimental database is needed and software tools detecting local feature size needs to be developed. At K.U.Leuven such tools are under construction [10]. The second approach is using optical sensors monitoring the melt pool continuously throughout the build process. At every moment during the build, these sensor give information on the melt pool (e.g. melt pool width or area) and incorporated in a real-time feedback loop, the process parameters can be adapted to obtain the desired melt pool properties. In this paper the second approach is followed. First the experimental setup of the optics and sensors is presented. For designing a stable and robust feedback controller, the dynamic relationship between the sensor output (e.g. melt pool area) and the process input parameters (e.g. laser power) is determined using experimental system identification. Based upon this dynamic model a stable and robust controller has been designed. The effect of changing the bandwidth of the controller will be discussed. Finally the use of the feedback controller will be demonstrated in two case studies and the use of feedback control in LLM will be discussed.

2. Experimental set-up

Figure 2 shows a schematic overview of the experimental setup [11] for monitoring of layerwise laser melting. This setup has been integrated in an in-house developed machine [12, 13]. Similar monitoring systems have been developed for other lase based production processes as laser cladding [14–16], laser beam welding [17–21], laser cutting [22] and laser hardening [23].

In our setup the laser source (4) is deflected by means of a semi-reflective mirror (3) towards a galvano scanner with focussing lens (2). The focussing lens of the scanner is a so called f-θ lens and has a focal length of 254 mm.

The radiation from the melt pool is transmitted through the f-θ lens, scanhead and semi-reflective mirror towards a beamsplitter (6), which separates the radiation towards a planar photodiode (8) and a high-speed CMOS camera (10). With the law of Planck it can be seen that the radiation energy at the melting point of metals (roughly around 1500K) is highest in the near infrared region, around 1000 nm. Figure 3 shows the reflectivity of a typical semi-reflective mirror coated for 1030 nm, in function of the wavelength. Since the reflectivity in a band around the central wavelength is nearly 100 percent, the melt pool radiation can only be captured in a range of wavelengths at a certain spectral distance from the wavelength of the laser beam, which is 1064 nm for the Yb-YAG fibre laser used in the set-up. Therefore the upper bound of the wavelength range to be captured by the sensors is choosen as 950 nm. The lower bound needs to

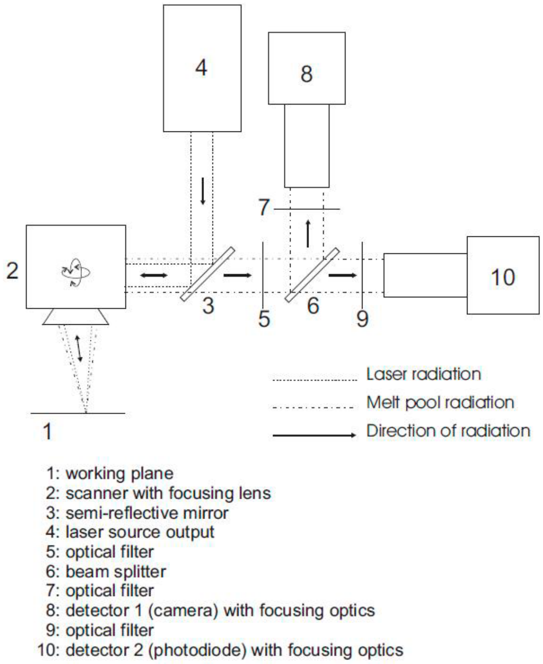

Fig. 2. Schematic overview of the experimental setup ot the monitoring system

be higher then 700 nm because visible light (from e.g. illumination in the process chamber) is not of interest for this set-up. Nevertheless the lower bound is still choosen somewhat higher (780 nm). The f-θ lens, necessary for focusing the laser beam on a flat surface, induces achromatic abberations for wavelengths others than 1064 nm. For this reason the bandwidth of the captured radiation energy cannot be too large: 780nm to 950nm is a good trade-off between the different demands. Finally a beam splitter separates the radiated light towards a planar photodiode and a high-speed CMOS camera. Both photodiode and camera are sensitive for wavelengths in the range of 400-900 nm, with peak sensitivity around 600 nm.

The high speed CMOS camera is no real thermal camera and only outputs a 8-bit grey value image. Nevertheless, the grey values given by the camera can be related to temperature and a correlation between the melt temperature of the used material and a so called melt grey value can be derived. Images of the melt pool have been taken while scanning a single scan track on a base plate with exactly one layer of powder. Afterwards the width of the scan track on the plate has been measured using an optical microscope. The grey value at which the diameter of a circle fitted at iso-greyvalues in the image is equal too the scan track width, is determined to be the melt grey value. The melt pool images are tresholded directly on the processing hardware of the camera into binary images: pixels having a higher grey value have a value of 1, lower greyvalues become 0. Based on the tresholded image melt pool properties as melt pool length, width and area can be derived using particle analysis algorithms. Throughout the build, signals as shown in figure 4 can be obtained. This figure shows the melt pool properties as area, length and width of the melt, together with the photodiode signal. It can be seen that the photodiode signal has a good correlation with the melt pool area. The major difference between the photodiode and the camera is the integrating effect of the photodiode (process light from larger zone around the melt is captured by the diode), while the camera gives only local information. It can be seen in figure 4 that the peaks in the photodiode signal are more flattened compared to calculated melt pool properties. However, hereafter the photodiode signal will be considered as a measure for the melt pool area.

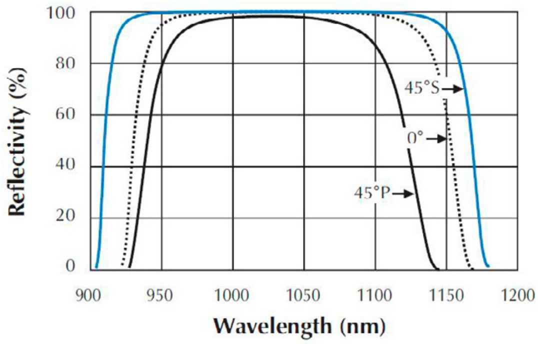

Fig. 3. Characteristics of the semi-reflective mirror

3. System identification and controller design

In other similar laser based production processes the integration of optical sensors in a feedback control loop has been studied: in laser cladding [16, 24, 25], laser surface modification [26], laser welding [27]. In this study the aim was to design a stable and robust controller based on the photodiode signal (representing the melt pool area) to give feedback to the laser power. It can be proved mathematically by deriving Planck's law to temperature for the wavelengths in the considered bandwidth, that the photodiode signal is almost not sensitive to the fluctuations of temperature in the melt, but very sensitive to changes in melt pool size. The laser power has been chosen as an adjustable input parameter because of the ease of changing it. Steering scan speed (i.e. steering the speed of the mirrors) is also technically possible using the XY2-100 protocol, however this will not be reported in this study.

The first step in the controller design is to identify the dynamic relations between the laser power and the photodiode signal. From both analytical models as the moving point source model [28, 29], as numerical models it can be expected that the dynamic relation between laser power and melt pool area can be approximated as a first order system. An identification experiment has been conducted, in which subsequent vectors parallel to each other have been scanned with constant scan speed. During the scanning of each vector, the laser power has been modulated with a multi sine function around the nominal laser power (in this case 42W). Figure 5 shows the multi-sine modulation signal with the frequency content. For each vector the photodiode response has been measured at a sample rate of 20 kHz.

Finally the Fourier transform of photodiode signals have been averaged in the frequency domain. Figure 6 shows the Fourier transform of the respons of one single vector, the averaged Fourier transform and second order model fit. It can be seen that the fitted model has a high correspondence with the measured data. It can be seen that the amplitude shows good correspondence over the whole range of excited wavelengths, while the phase only shows good correspondence until 1500 rad/s. The real phase decreases further then -180, while obviously the second order system cannot.

Based on the second order model fit, a PI controller has been designed. Some practical considerations have been taken into account:

- the bandwidth of the controller cannot be too high since the photodiode sensor is sensitive to 'sparks' escaping the melt pool, yielding high frequency noise in the photodiode signal.
- Only limited derivative action can be used, due to the noisy photodiode signal.

Three controllers with different bandwidths have been designed and tested, see figure 7. The first controller has a bandwidth of 3600 rad/s (very fast reaction), the second 660 rad/s (intermediate reaction) and the third one , of 95 rad/s (slow reaction). As figure 7 shows, the first controller leads to overshoot at the start of a vector and overreacts at noise due to sparks from the melt pool. The third controller reacts too slow on disturbances. Further in this study, the middle controller will be used.

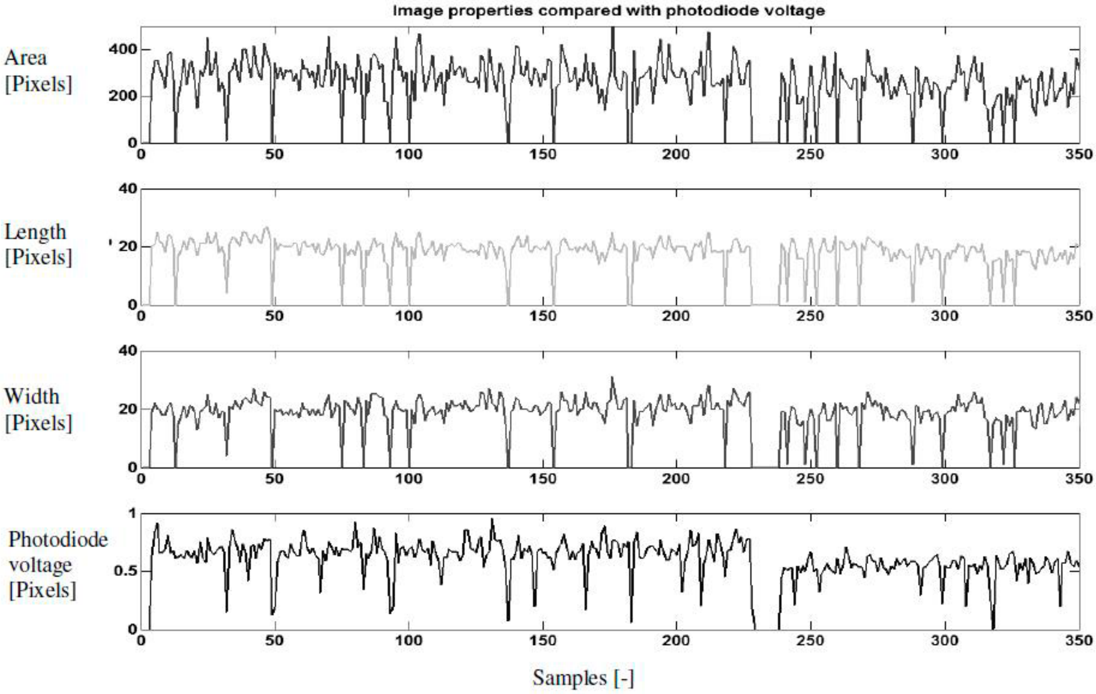

Fig. 4. Typical output of the process sensors: melt pool area, length and width and the photodiode signal

4. Experiments

To test and validate the use of a feedback controller in layerwise laser melting, experiments have been performed. Feedback control of the process only has advantages in three different scenarios:

1. In case a process problem occurs (e.g. excessive oxygen in the process chamber), feedback control of the process parameters cannot always solve the problem, but in most cases can lead to a significant improvement.
2. In case of scanning downfacing surfaces, overheating can occur. To counteract this problem, some machine vendors allow choosing different process parameters or scan strategies for these surfaces (i.e. feedforward control). However, the feedforward estimate of appropriate local process parameters in most cases needs to be corrected with feedback based on in situ measurements of the melt pool dimensions.
3. In case very thin structures with controlled feature size need to build, monitoring the melt pool width and giving feedback to the laser power can broaden the window of features which can be produced with LLM.

In this research a benchmark study of the first two scenarios has been performed and the use and advantage of feedback control will be demonstrated.

4.1. Scenario 1 - process problems: processing of cubes with small scan spacing

This case study is a benchmark for the first scenario. Three cubes have been processed with fixed process parameters: scan spacing of 0.035 mm, laser power of 42 W and varying scan speed (100, 300 and 700 mm/s); see figure 8 at the top. Since the scan spacing was small, the surface of the produced samples shows a large waviness, due to thermal deformations in the processed layer. The part with the highest scan speed could not be build completely due to the overly high surface roughness. The parts produced with feedback control show a significantly improved surface roughness, see figure 8 at the bottom. The laser power is diminished by the controller when overheating starts to occur. Figure 9 shows the photodiode signal in case of uncontrolled (see figure 9 left) versus controlled (see figure 9 right). It can be clearly seen that the controller reduces the laser power to counteract the overheating.

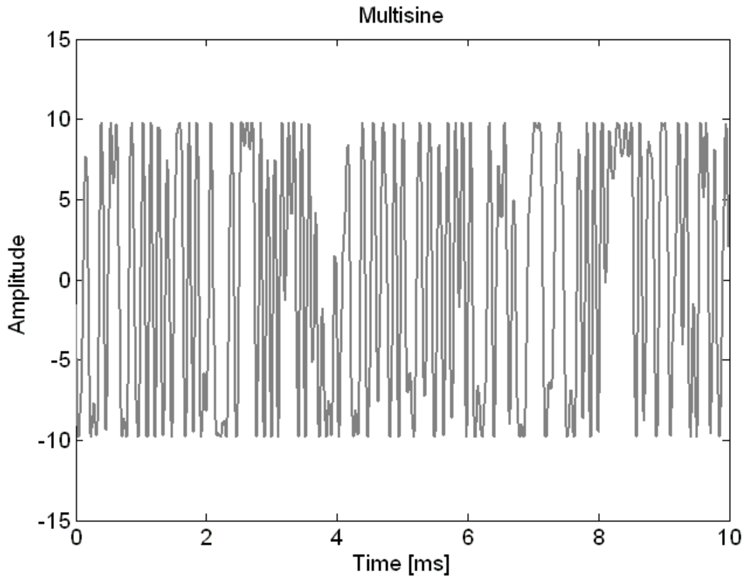

Fig. 5. The multisine function in the time domain used in the identification experiment for modulation of the laser power around the nominal value of 42 W. Length of one scan vectors was 30 mm and the scan speed 225 mm/s. The sample frequency was 20 kHz. 1

4.2. Scenario 2 - downfacing surfaces: round overhang structures

Overhang structures are zones within a layer where the melt pool is located above loose powder material, having lower thermal conductivity than the corresponding bulk material. These zones have a small heat sink, compared to when the melt pool is above bulk material. When static process parameters are used throughout the build, local overheating will occur in these zones. This leads to dross formation and bad surface roughness, but also to differences in local microstructure since the cooling down rate of the melt pool drastically changes. In this study round overhangs with a diameter of 8 mm have been considerd. Figure 10 on the left shows a round overhang structure scanned with fixed process parameters. The dross formation can be seen at the top of the cylindrical hole. On the right the overhang with feedback control is shown. The surface quality of the round overhang is significantly improved. Figure 11 shows the photodiode signal in the open loop experiment, compared to the closed loop experiment. In case of open loop the melt pool size increases drastically, while in the closed loop setup the melt pool dimensions are only sligthly increased. In the future the combination with a priori knowledge (feedforward control) and in situ monitoring with feedback control will be investigated for further improvement of the surface and material quality.

5. Conclusions

This paper presented feedback control in layerwise laser melting. In the LLM process nowadays the process parameters as laser power and scan speed are optimised for a certain material on a certain LLM apparatus, generally to obtain maximum density and surface quality. During the build process the process parameters are kept constant. However, the local geometry surrounding the melt pool largely influences the melt pool size. With the use of static process parameters at downfacing surfaces, the melt pool grows too large, leading to bad surface quality at these planes. The optical sensor used for process monitoring in this study was a large area planar photodiode. The analog output signal from this sensor is strongly correlated with the melt pool area. Further the dynamic relation between the laser power and the photodiode signal has been determined as a second order system, using experimental system identification. Based on this dynamic relation a feedback controller with optimal bandwidth has been designed.

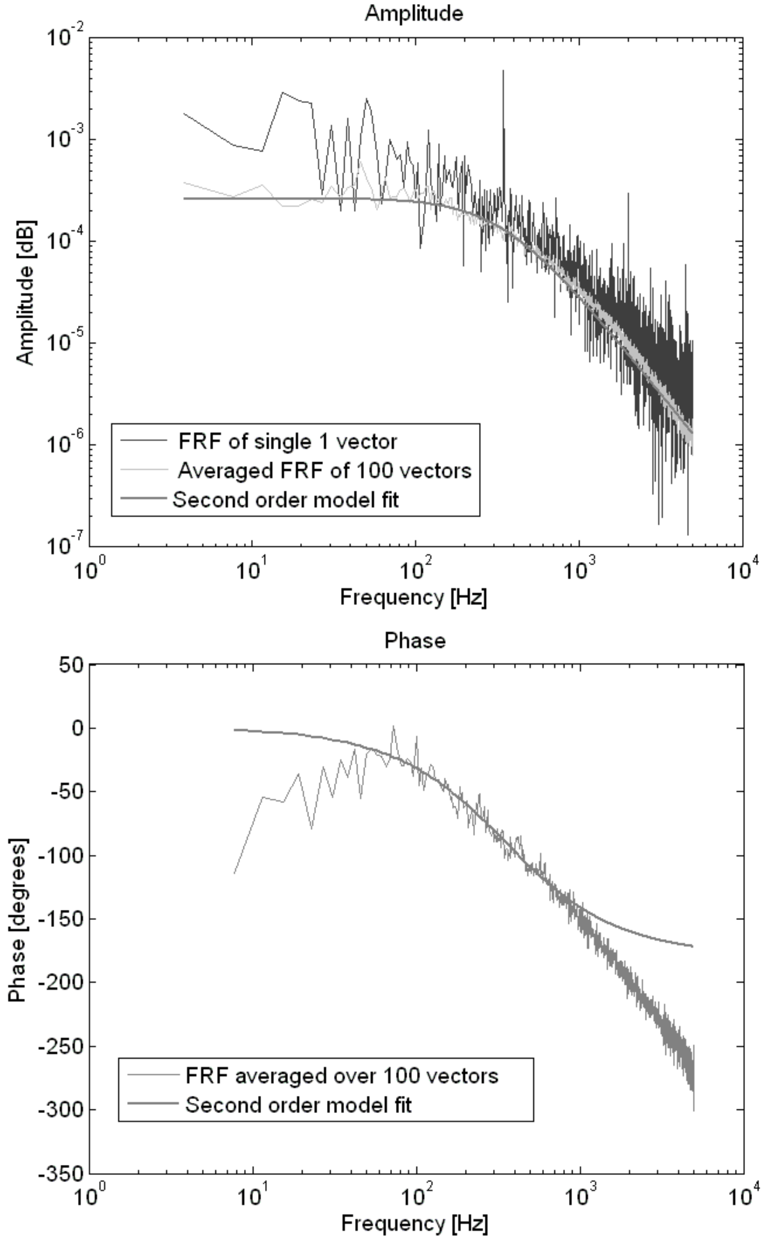

Fig. 6. The amplitude spectrum of photodiode response of one vector and the averaged Fourier transform of 100 vectors. A second order model is fitted through the experimental data. There is good correspondence both for amplitude as phase, however the measured phase passes -180 degrees and obviously the fitted second order model does not.

The use of a feedback control has been demonstrated in two benchmark studies: bad process conditions - in which feedback control leads to a significant improvement - and overhang structures - in which the use of feedback control can improve the quality of the downfacing surfaces.

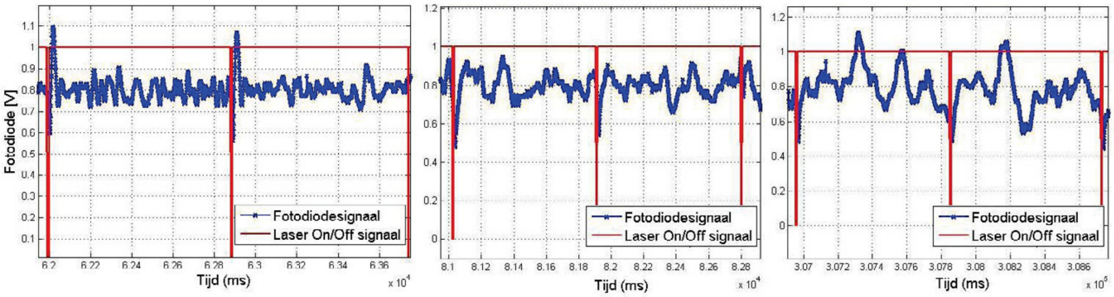

Fig. 7. Photodiode signal during scanning using controllers with three different bandwidths: 95 rad/s, 660 rad/s and 3600 rad/s

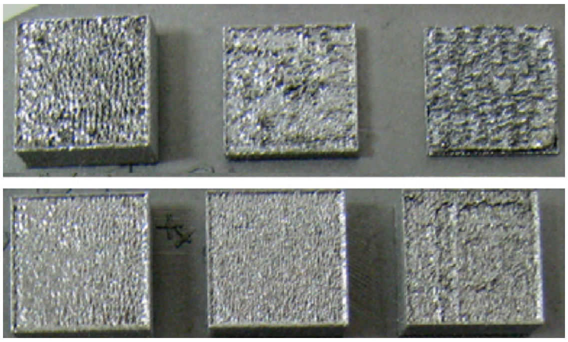

Fig. 8. Processing of cubes without (top) and with (bottom) feedback control

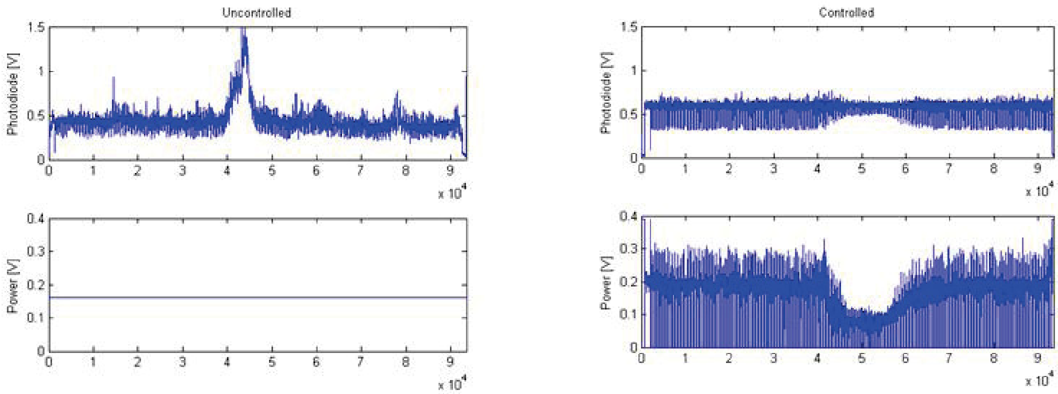

Fig. 9. Laser power during scanning of the cubes. Overheating occurs without feedback control (left)

Future tasks are to control the process based on real-time image processing, based on images from the high speed camera. Dedicated image processing hardware for this task is under development. Furthermore control of laser scan speed is an economically more interesting parameter. Last the combination of using a priori knowledge on the geometry (feedforward control) in combination with feedback control will be investigated for optimisation of overhang structures and broadening the process window for thin features.

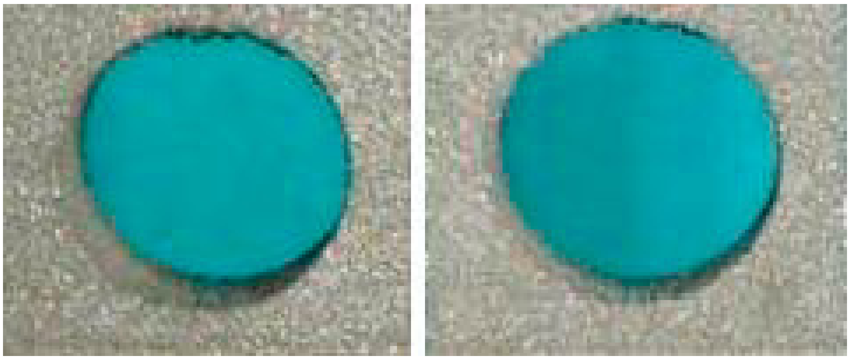

Fig. 10. Round overhangs: on the left without, on the right with feedback control. Without feedback control overheating at the downfacing surface leads to dross formation and high surface roughness. With feedback controll the dross formation is reduced significantly.

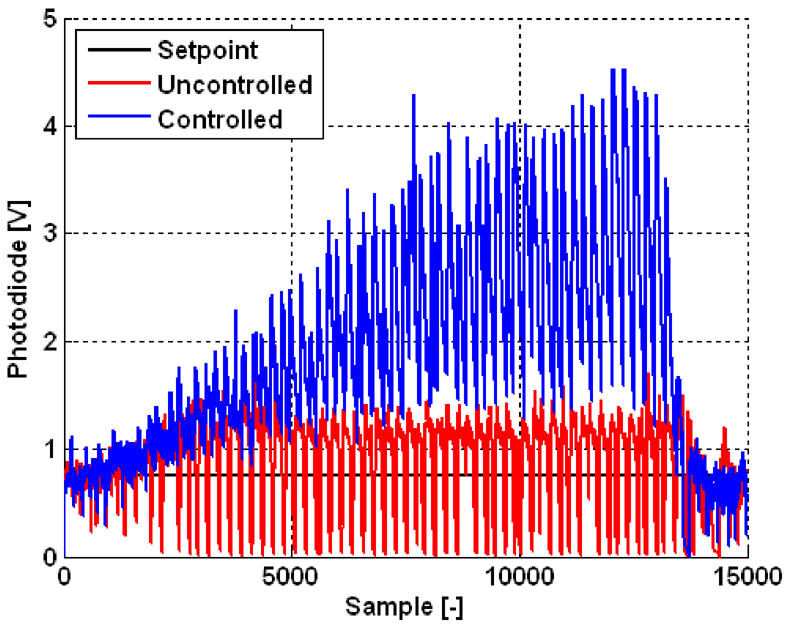

Fig. 11. Laser power while scanning round overhangs: with fixed laser power the melt pool size increases drastically. Feedback control keeps the melt pool size approximately constant.

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