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# Identification of process phenomena in DMLS by optical in-process monitoring

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## Abstract

Additive manufacturing processes of metals were investigated by an optical in-process monitoring setup.
Direct Metal Laser Sintering (DMLS) is an AM-process in which parts are built from metal powders, which is fused layer by layer, through exposure with an infrared laser.
The basic layout of the monitoring setup is photodiode-based sensing of process light in combination with software-based data evaluation of the photodiode signals.
Enhancing a monitoring or measuring system for the purpose of automatic quality inspection requires sufficient knowledge about the correlation between involved sets of variables. In this context, variables were partitioned into three categories: input variables (meaning the process control e.g. laser power, scan speed etc.), material properties and photodiode signals including their signal characteristics.
Correlations between monitoring signals and process conditions were found, based on a comparison of nominal process (baseline population) and faulty process (defect population).
Faulty process was induced by intentional variation of the input parameters (provoked errors, e.g. variation of laser power), as well as investigation of known and  undesired process effects (e.g. overheat effects, interaction of laser beam and process smoke). Characteristics in the corresponding photodiode signals were identified.
Algorithms to auto-recognize these signal characteristics were created and tested successfully . Examples are given that show the successful auto-detection of selected process effects.

Keywords: Additive manufacturing; Process Monitoring and Control

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## 1. Introduction

A few years ago, 3D printing and Additive Manufacturing (AM) technologies were next generation technologies and well known methods for rapid prototyping. Today, AM is on the step to serial production, industries ranging form aerospace and medical to energy and automotive benefit from the possibility to design and manufacture products in a completely new way. These industries require a detailed documentation of the process including automated in-process quality inspection.

This paper describes how an optical in-process monitoring system for DMLS process can be set up and used for purposes of process understanding and quality assurance.

## 2. DMLS Process

Direct Metal Laser Sintering (DMLS®) is an AM process in which digital 3D design data are used to build up a component in layers by depositing metal material. The system starts by applying a thin layer of the metal powder material to the building platform. After each 'recoating' a laser beam then fuses the powder at exactly the points defined by the computer-generated data, using a laser scanning optic. The platform is then lowered and another layer of powder is applied**Fehler! Verweisquelle konnte nicht gefunden werden.**. Once again the material is fused so as to bond with the layer below at the predefined points resulting in a complex part. Thereby not only the part but also the final material is created in the process and defines the unique characteristics of this technology. Every single welding line creates a new micro segment of the final part, and the welding process can be monitored.

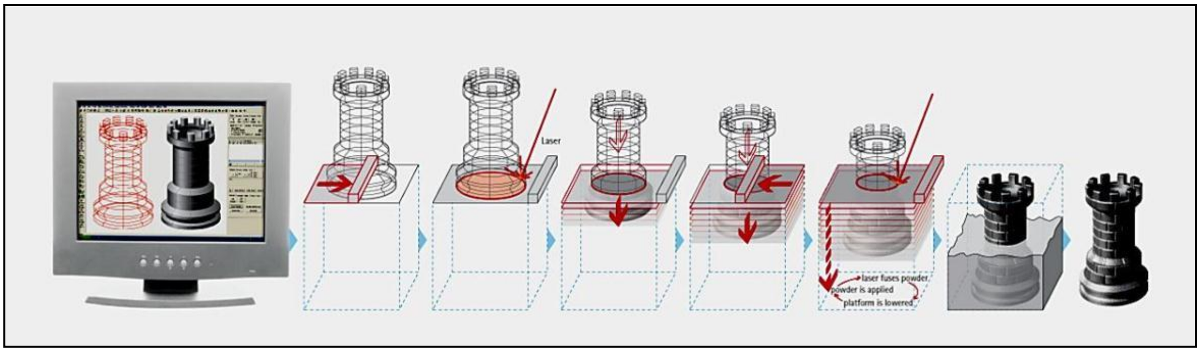

Fig. 1 Description of DMLS process

## 3. Photodiode-based in-process monitoring - basic layout

The monitoring setup uses photodiode based sensors to collect light emissions emerging from the process. Two photodiode based sensors were integrated in the machine, the first one being located above the process area in 'Off-Axis' configuration. The second sensor is mounted in 'On-Axis' configuration, i.e. coupled collinear with the laser beam, using a semi-reflective mirror. In this case, the monitored process light passes scanner and machine optics.

In both cases, silicon photodiodes were used, spectral sensitivity being in the visible and near-infrared range, approx. 400-1100 nm. The basic setup allows integration of other photodiode or sensor types, therefore it is possible to use a different wavelength range in future applications.

Adequate spectral filtering is used for each photodiode, to block out laser light and minimize the influence of ambient light.

In addition to the sensors, the monitoring system has an interface to the machine control, receiving various data on machine status, scanner position, laser status and part geometry data. This additional information is useful for data visualization and data analysis.

A software has been created to analyze and and evaluate the photodiode signals and visualize the results. After teaching the software accordingly, it was possible to get automated OK / NOK assessment of the DMLS process under certain conditions.

## 4. Using the in-process monitoring system and setting the system up for quality inspection

The defined goal of an in-process quality inspection system is the ability to indicate if the process output deviates from the nominal state. In case of DMLS process, the relevant output parameters are material and part properties such as tensile strength, porosity, surface roughness etc. Since it is impossible to directly measure these parameters by an in-process measurement, it is necessary to identify indirect, correlated variables.

Light emission from the process can be considered as 'process output variable'. It is practical experience that light emissions can indicate process behavior and also process failures. Process light can be captured by the optical in-process monitoring system, and our work proves that certain characteristics in the signals can be used to judge the process quality and detect failures.

There are various methods to identify corellation between signals and part properties. The best case would be to have a complete (mathematica)l model of the process and all involved variables. However such a model does not exist yet.

It is therefore appropriate  to use some kind of empiric approach.

One heuristic method of  is comparison of actual monitoring data with reference data that have been obtained from OK process. Any deviation will be considered as NOK. This approach is impracticable for DMLS, because a huge amount of reference data would be necessary due to the amount and complexity of laser paths varying from part to part and from layer to layer.

It turned out that of black box testing accompanied by some process model concepts, is a successful approach.

DMLS process is considered to be a 'black box' with a quantity of input and output variables.

The basic idea is to to run an OK process to create a baseline population of signal characteristics, and then provoke NOK process states. It turned out that signal characteristics could be identified that correlate with the process. It turned out to be helpful for test design, if input and output variables are sub-classified and categorized in real malfunctions and unwanted process effects. See Fig. 2.

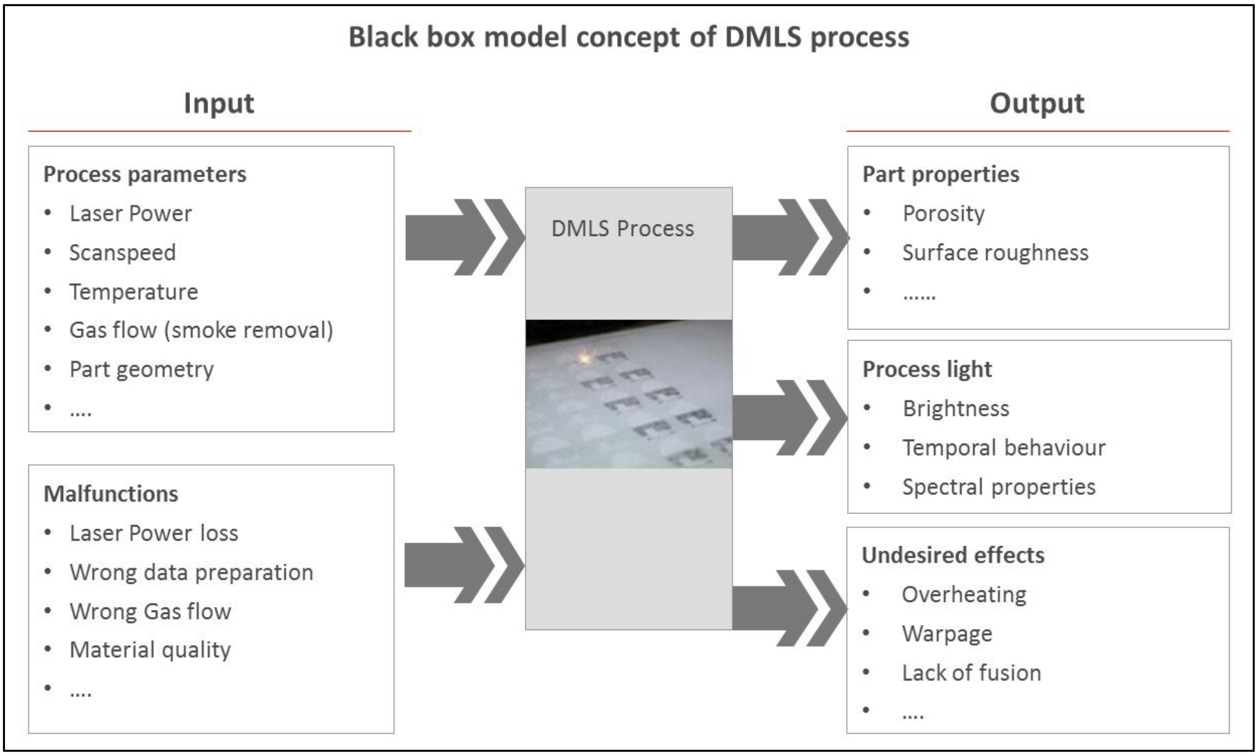

Fig. 2 Black box model of DMLS Process with input and output variables

Signal characteristics can be calculated from the raw signals in time-, frequency- and time-scale domain. Typical features from classic remote welding [1] can be used, e.g. moving average, short term evaluation and signal dynamics, which can be calculated in hard real time.

It is relatively easy to create baseline population: Standard process parameters are considered to be 'OK'.

There are various methods of creating process deviations and 'NOK' process. One usual procedure is systematic variation of input parameters e.g. energy input (laser power and scan speed). DOE (design of experiments) methodology can be used, and investigation of the created material can be included (e.g. a sensitivity analysis how porosity corellates to energy input).

A side benefit of this method is increased knowledge about the process. However with regards to the objective of quality inspection, the results will be not completely satisfying. Some of the investigated parameters are unrealistic to happen in real machine operation. E.g. deviation of scan speed is a very unlikely failure mode in a digitally controlled scan system.

Based on sufficient know-how it is possible to provoke errors and phenomena, which directly address problems and failure modes that are known from real life. Two examples are given.

## 5. Examples

### *5.1. Incomplete recoating*

This is an example of a malfunction, usually caused by incorrect operation of the machine, e.g. choosing a too low dosing factor. There may be reasons why a dosing factor as small as possible is indented.

Provoking this failure and setting up the test can be done easily. In our case a job was set up with several cylinders, arranged in three and a half rows. See Fig. 3 Low dosing factor was adjusted, causing incomplete recoating on the left side of the building platfom. Signals from the subsequent laser exposure were analyzed. The cylinders on the right side of the build platform (which have been recoated correctly) served as baseline population. Cylinders on the left side reproduce the NOK case.

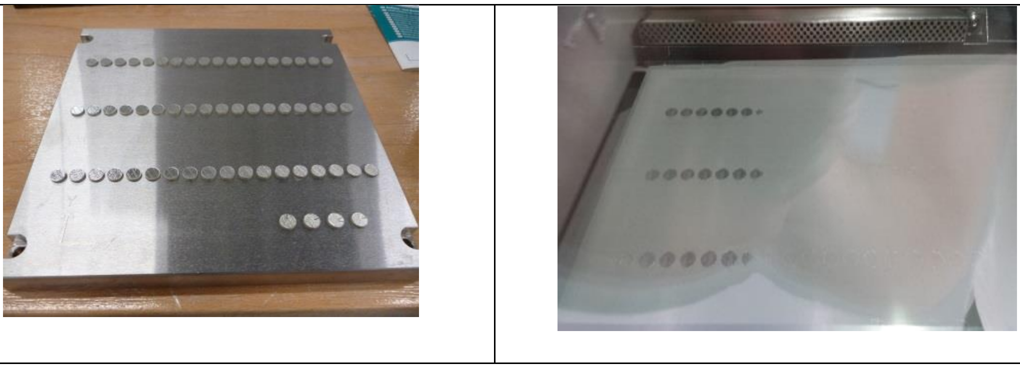

Fig. 3. (a) Job with several cylinders; (b) Incomplete recoating (provoked error)

A first inspection of the photodiode signals resulted in different signal levels and characteristics. Suitable evaluation algorithms were chosen and parameterized. Soon an automatic classification of OK and NOK recoating could be shown, and visualized in an OKNOK map of the layer (Fig. 4a). The displayed paraemter is the probability for OK or NOK, visualized as color axis from green (OK) to red (NOK). With some fine-tuning of evaluation parameters, a sharp distinction of OK and NOK recoating was archieved. See Fig.4b.

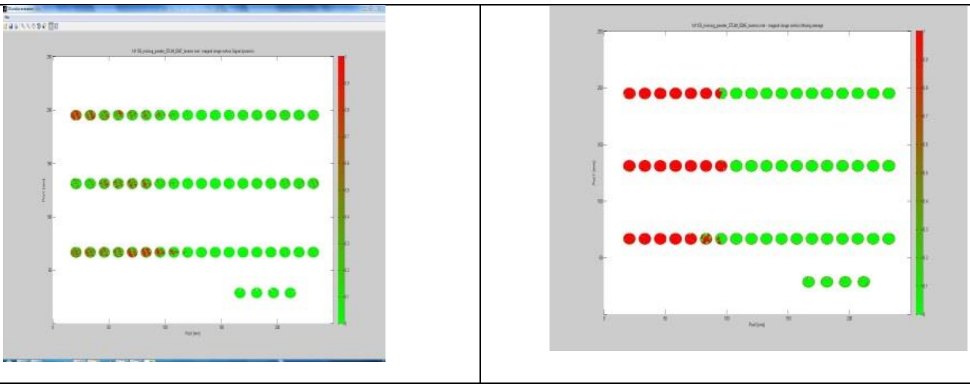

Fig. 4. detection if incomplete recoating (a) suboptimal parametrisation ; (b) optimal parametrisation

### *5.2. Process flipping*

From experience it is known that the process sometimes can look 'NOK', creating lots of 'splashes' and fluctuating light emissions. The melted material looks different, increased surface roughness can be observed.

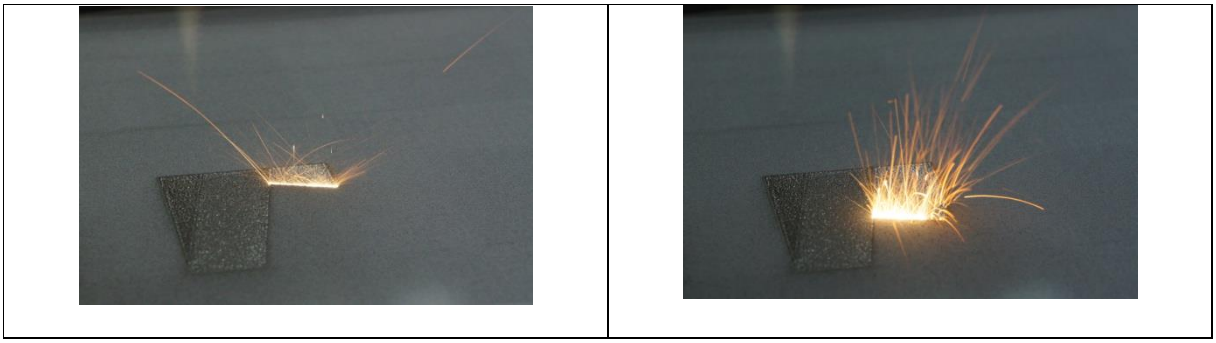

Fig. 5 Process flipping. (a) normal process; (b) process irregularity

Defocussing of the laser beam had been identified as origin of this phenomenon. There are different ways how the defocusing can happen. In real life, interaction between smoke and the laser beam can cause this effect. This happens especially if the laser beam and smoke move in the same direction. If this process anomaly happens rarely enough, it has no negative consequence on part quality, because the rough surface will be re-melted in the next layer. However if the preocess irregularity happens steadily, material properties can suffer [2].

In order to create a defect population, this effect is inconvenient because smoke creation is a random effect and it's difficult to reproduce the irregularity reliably.

We decided to choose another method to create irregular process. We found that the process reacts on alteration of focal position in the same way as on smoke interaction. (This leads to the conclusion that the predominant effect of smoke and laser interaction is an alteration of the laser spot size, as predicted by Rayleigh scattering).

In this example we changed the focus position round about one Rayleigh-length. A Job was set up containing several parts that are used for material analysis: bars for tensile testing, and cubes used for cross-cuts and porosity analysis. The provoked effect parts were arranged in three bars in the left corner of the built platform. Instead of cubes we built here three parts with a letter “F” embedded. See Fig. 6. It is good practice to build embedded parts when experiments with provoked errors are performed - mitigating the risk of disturbing or crashing the entire build job.

During build, a slight deviation of the process emissions was visible with the plain eye. After finishing the job, slightly higher surface roughness was found on the 'defocussed' tensile bar samples. The difference in surface roughness is small, it is visible by manual inspection but can’t be seen in the photograph Fig. 6a.

Different approaches exist to detect noisy process. One possibility well known from classic laser welding and laser remote welding is signal dynamics [1], detected by a special implementation of windowed variance. By comparing the baseline and the defect population limits could be found to distinguish between OK and NOK process in time-resolved signals and indicate the probability for OK and NOK. Fig 6 b. shows the resulting OKNOK map of one layer of the building job. Color axis indikates the probability for OK (green) and NOK (red). The provoked process irregularity has successfully been detected in the bars in the left lower corner and the embedded letter "F" .

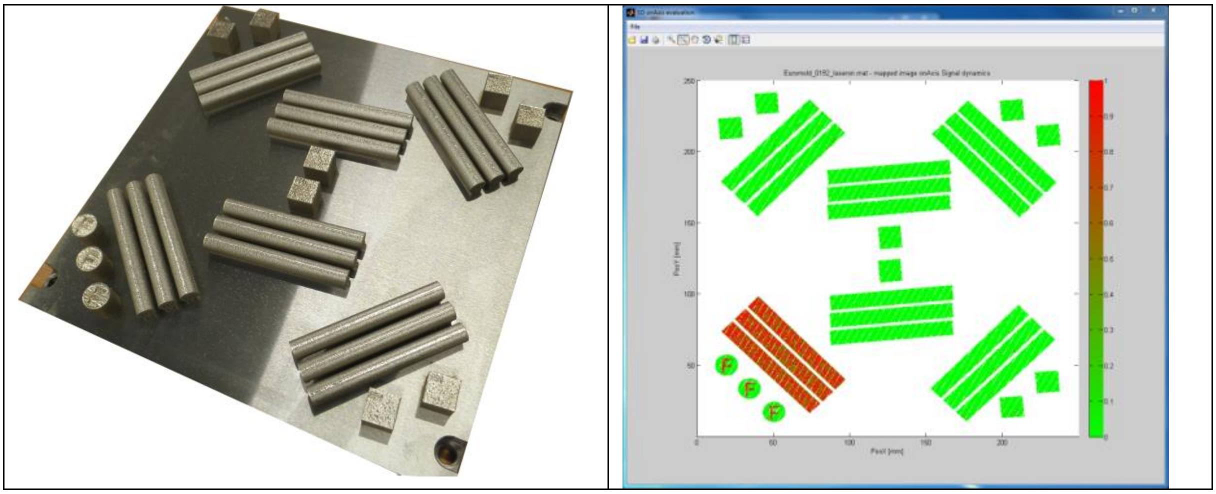

Fig. 6 (a) Job setup 'process flipping' (provoked error); (b) detection of process flipping

## 6. Summary

A concept of setting up a quality inspection system for the DMLS process is shown using photodiode based optical in-process inspection and software based signal evaluation. A method is presented how this this system can be set up for quality inspection. Examples are given that previously provoked process failures (incomplete recoating, 'process flipping') could successfully be detected.

## References

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