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Low coherence interferometry in selective laser melting

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Abstract

Selective Laser Melting (SLM) is an additive layer manufacturing technology that offers several advantages compared to conventional methods of production such as an increased freedom of design and a toolless production suited for variable lot sizes. Despite these attractive aspects today's state of the art SLM machines lack a holistic process monitoring system that detects and records typical defects during production. A novel sensor concept based on the low coherence interferometry (LCI) was integrated into an SLM production setup. The sensor is mounted coaxially to the processing laser beam and is capable of sampling distances along the optical axis. Measurements during and between the processing of powder layers can reveal crucial topology information which is closely related to the final part quality. The overall potential of the sensor in terms of quality assurance and process control is being discussed. Furthermore fundamental experiments were performed to derive the performance of the system.

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Keywords: Selective laser melting (SLM); Laser beam melting (LBM); Low Coherence Interferometry (LCI); Process monitoring; MEGaFiT

1. Introduction

Selective laser melting (SLM) also referred to as laser beam melting (LBM) is a rising manufacturing technology. A weldable powder material is fused layerwise to the final part using the power of a laser beam. This additive building technique offers an increased freedom of design compared to conventional machining which is an advantage for light weight designs as required in transportation and aviation in particular (Emmelmann et al. (2011a)). Another process-related advantage is the dissociation of production costs and part numbers. This is attractive for industries where individual products are being produced in small quantities such as prototype construction or prosthetic dentistry. The additive manufacturing process also allows the production of lattice structures that makes the technology attractive for the manufacturing of medical implants (Rehme (2010), Emmelmann et al. (2011b)). A major downside of today's SLM technology is the lack of holistic approaches for quality documentation inside the SLM machines. For a given powder system and layer size the process parameters consisting of laser power and scan speed are determined in experiments. In this experiments typically cubic test specimens are being built and the resulting quality parameters are examined. Results gathered during this initial production do not always apply to the produced parts. There are

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several important influencing factors that result in defects that are not observed during the initial process studies. One important factor is the condition and particle size distribution of the powder material that might change from job to job (Seyda et al. (2012)). Another factor is the specific geometry of the part produced. Depending on the material distribution and the scan strategy temperature induced stresses deform the part and can even lead to cracks and dissolution of layers (Munsch (2013)). Thus even side samples may not represent the quality of the actual part in every case since they are produced on another position of the build platform and have a different geometry. The work presented is part of the *MEGaFiT* project funded by European Communitys Seventh Framework Program. The project aims at a zero-defect manufacturing of complex high-precision metal parts (*www.megafit-project.eu*). An adaptive control approach is being developed and demonstrated by means of two case studies, a multi-stage mirco-forming process and the additive manufacturing technology of SLM discussed in this paper. Among other sensors the control system for the SLM process uses a scanning sensor concept based on low coherence interferometry (LCI). This coaxially mounted sensor is able to detect surfaces and at the current status of development already promises to be able to detect defects and deviations in the manufacturing process that might lead to defects later on. The novel interferometry setup presented in this paper has been patented by the *Precitec Optronik GmbH*.

2. State of the art in SLM process monitoring

There are several approaches to ensure the quality of SLM parts during production. They can be separated into systems that locally monitor the melt pool and systems that monitor the whole build platform. The ones that operate on a local scope usually measure the visible or infra red emission coming from the melt pool. They are either spatially integrating diode and pyrometer systems or camera based solution (Bayle and Doubenskaia (2008), Craeghs et al. (2012)). These systems are able to document the melt pool size during the production process. The information of interest coded in form of signal amplitudes can be corrupted by weld fume, disposals on the optics or spatter. Locally operating systems are not able to cover the whole bandwidth of possible defects within the production process. Defects that occur after solidification such as dissolution of material several layers below the current one and part deformation can hardly be detected, if at all. The sensors used have to be combined with other sensors to cover the whole process. Systems operating on a global scale are often cameras in the visible and infrared range. A sidewise mounted illumination can reveal surface deviation within the powder bed or solid material. This can be used to monitor the powder bed or characterize the structure of melted regions (Kleszczynski et al. (2012)). Thermography cameras can capture the cooling rate of the surface and thus are also able to detect defects within the powder layer as Krauss et al. (2014) demonstrated. Another sensor concept that works globally is an acceleration sensor that has been integrated into the coating unit presented by Kleszczynski et al. (2014). Each interaction between the coating unit and solid material sticking up results in strokes detected by the sensor. Since the coating unit is a linear structure the signals cannot be traced back to a certain point along the line. Another problem is the wear of the coating unit. With each collision the profile changes what might limit the long term validity. A global approach that comes close to the interferometry sensor presented in this work is the fringe projection. It also captures the surface profile. There are two differences worth mentioning regarding the integration into the machine. Firstly the topography sensor based on LCI is mounted coaxially to the processing beam. The coordinates of the material processing and the monitoring are the same. No coordinate transformation is required as in a off-axis setup used for fringe projection. Secondly the interferometry sensor samples the surface sequentially. This means that the duration of a measuring task strongly depends on the area covered. Schmitt et al. (2012) developed a interferometry sensor for application in laser ablation that is similar to the one examined in the work at hand. Different from the *MEGaFiT* setup an F-Theta optic has been used.

3. System Setup

3.1. SLM setup

The SLM setup is based on a *EOS M250* machine. The original CO_2 laser beam source was replaced by a *ROFIN FL010S* 1 kW fiber laser. The beam is collimated by a optoscand QB d25 f91 module. For deflection and focusing of the laser beam a *SCANLAB intelliSCAN 30* and a *varioSCAN 40* with a focal length of $639\,mm - 712\,mm$ are being used. The scanner has a working distance of 520 *mm*. The control of these units happens via a *SCANLAB RTC5 PCI* controller board. Besides of the standard mirror coating for the processing wavelength λ_p of 1070 *nm* the deflection mirrors of the scanner have an additional coating for the sensor wavelength λ_s of 880 *nm*. A beam splitter couples the sensor light onto the axis of the processing laser as displayed in figure 1.

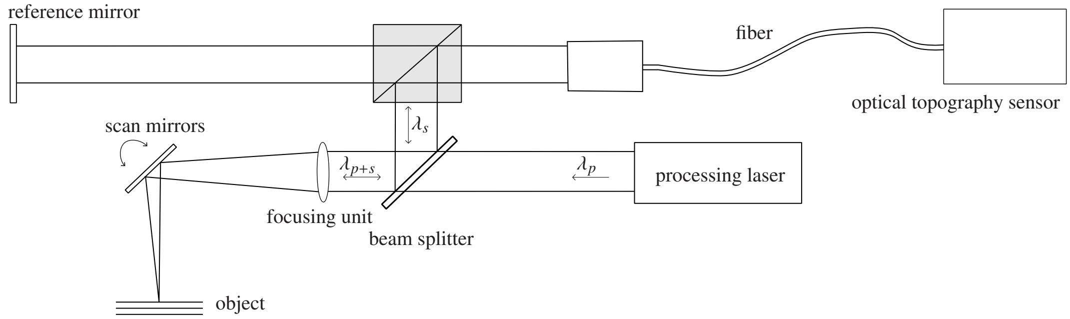

Fig. 1. Integration of the interferometry sensor into the optical setup of the SLM machine.

3.2. Sensor setup

The optical sensor is based on the *PRECITEC IDM sensor (www.precitec.de)*. The maximum scan rate of the device is 70 *kHz* and complies with the requirements in SLM. The measuring principle is based on the low coherence interferometry principle. The topology to be captured is actively exposed to the radiation of a broadband light source. The acquired signals are transferred to a distance information which can be accessed either at the analog output (16-bit resolution), via USB or via a serial connection in real-time.

4. Possible applications of LCI based sensors in SLM

As mentioned in the introduction the sensor in this work does not capture the whole build plane at once but uses the scanning unit to sample the surface topography sequentially. For each application in SLM a specific scan strategy has to be defined. Depending on the measuring task data acquisition takes milliseconds for single points and several seconds for larger areas.

4.1. Setting up the SLM machine

There are several applications during the setting-up of the SLM machine where the interferometry sensor could possibly be used to reduce the defects of parts and the frequency of process interuptions. Furthermore, the rigging procedure could be quickened.

Properties of the build platform: The build platforms that carry the parts during the production process are being used for a great number of jobs. After each job the parts are removed for example by wire-cut EDM machines and flattened in a milling process. To assure a solid connection between the platform and the part to be generated, the first powder layer has to have a defined constant height. The optical sensor based on LCI could assure the flatness before each job is started and also could confirm that the platform is not mounted tilted. For this task just a few sampling points are required since the expected deviations have a rather low spatial frequency.

Determination of the focus position: For minimal resolution during the exposure of powder layers the focal position of the laser beam should match the surface plane. This also makes the process more robust against focal shift due to thermal distortions of optical components. To adjust the SLM machine setup according to this requirement surface scans of different focal positions are performed and compared manually. The LCI based sensor could be used to execute this task automatically by analyzing the profiles of single weld beads.

Application of the first powder layer: The application of the first powder layer is until now an imprecise procedure that strongly depends on the operating personnel as it is done by visual inspection. By comparison of several reference measurements the sensor could perform this task automatically. Figure 2 shows one possible way to proceed: Before applying the powder the platform is placed at a level significantly lower than the expected position. The optical sensor now measures the distance A to the surface (2a). Afterwards a powder layer is applied and the level B of the surface which coincides with the level of the coater tip is sampled (2b). A defined thickness D can now be achieved by moving the platform upwards based on the values measured before. Finally the excessive powder volume will be removed by the coating unit (2c). A defined first layer size is expected to make the process outcome more deterministic compared to today's manual procedure.

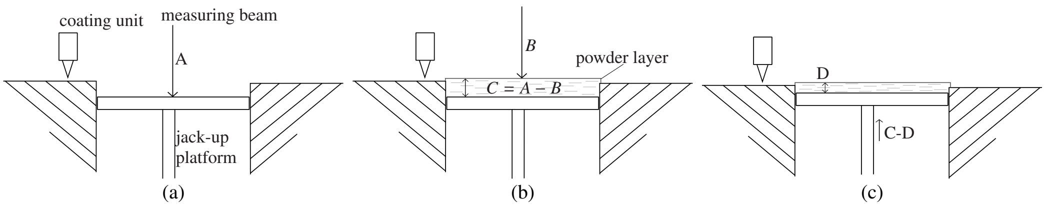

Fig. 2. Application of a defined powder layer: Detect build platform (a), apply an oversized layer and detect powder surface (b) and remove excessive powder material (c).

4.2. Monitoring of single layers

Within the cyclic laser beam melting process several properties of each layer can be determined. These measurements increase the overall build time since they occupy the scanner and pause the material processing. The gained information can be used to assure the layer quality, prevent the coating unit from suffering damage and abort single defective parts during production to reduce the production time and material waste.

Inspection of the powder bed: During the SLM process the coating unit tends to wear of due to collisions with material sticking up above the trajectory of the coater unit. If the unit has been damaged locally, powder traces of increased layer size will result oriented along the coater motion. These powder traces will corrupt the quality of the part significantly. in some cases also problems with the powder supply occur. Empty powder containers and reduced feed rates of the powder hopper cause defects that both lead to deformations of the parts produced. Where today the attention of technical personnel is needed to check on those issues the optical sensor could check for surface deviations. Another process that could possibly be observed is the erosion of powder material caused by the gas circulation.

Inspection of core regions: During the processing of core regions one possible deviation from an ideal melting process is caused by changes in heat flux. In core regions the heat conduction of solid material is assumed. If there are powder volumes in one of the layers below the current one, overheating of the melt pool occurs and the actual part suffers damage caused by increased melt pool size or increased spatter. The LCI based sensor could be used to detect these damages. An automated way to monitor the core regions could be realized by means of indexes that correlate with the layer surface quality as described below in chapter 5.3.

Inspection of contour regions: There are mainly two kinds of defects that could be detected with an LCI based sensor at the contours of a part: Elevated ridges and part deformations. Elevated ridges are closely related to the melt flow. They reduce the surface quality and are likely to damage the coating unit (Yasa et al. (2009)). A surface acquisition of the outer contour can document the degree of elevation. Moreover, part deformations can occur due to the thermally induced stresses during the laser melting process. Deformations within the x-y-plane of the build platform could be detected if the sensor is able to distinguish between powder and solid material based on the signal patterns observed. Parts bended upwards along the z-axis could be detected if not only the outer contour is scanned but also some offset contours towards the core. This way it can be determined if larger regions are elevated.

4.3. Monitoring of the melt pool

Generally, a heat conduction welding process is desired in selective laser melting. The melt pool has a low aspect ratio of approximately one. With increasing power density and rising temperatures of the melt pool the process changes and deep penetration welding can be observed (Assuncao et al. (2012)). The surface of the melt pool caves in and a so called keyhole is formed resulting in deep narrow weld tracks with high aspect ratios. Within SLM this phenomena must be avoided since spatter rate increases, the subjacent layers would be remelted and contours of the part be damaged. Usually this should not happen for a developed set of parameters. However, certain geometrical situations with high powder content near the melt pool and thus reduced heat flow could evoke this event. If optical reflections from the key hole could be received during the material processing these signal patterns could be used for an online control that reduces the laser power input and thus prevents deep penetration welding defects.

4.4. Accelerated parameter studies

Today, the development off suitable process parameters for laser melting of different powder materials is often a time-consuming and rather manual procedure. Cube specimens are being built with a fix combination of parameter pairs on a platform. Afterwards quality indicators like the density and the surface roughness of the specimens are being analyzed in a lab environment. The LCI based sensor might be able to provide layer based information that is related to the final part quality. This would be done already within the machine without even taking out the specimens. This obviously would not replace the analysis of quality criteria in the lab. But a parameter window might be determined much faster if the iterative loop of processing and qualifying the results happens within the machine. An adaptive algorithm could vary the parameters tested based on topography signals gathered by the *PRECITEC* sensor before. This would increase the efficiency of experimental studies during the first stage of single layer formation.

5. Experiments and Discussion

5.1. Measuring range

To determine the measuring range of the sensor a surface scan along the y-axis is performed on top of the build platform holder. Figure 3 displays the profile obtained. The scan shows that the sensor output for the distance measured is about $0\,\mu m - 2900\,\mu m$. Along the scan the profile has a parabolic character. At the central position of $x = 0\,mm$ the distance from the deflection mirrors to the accidental point of the measuring beam is minimal. While moving away from this position this distance increases due to the pivot-mounting of the mirrors. This applies for every direction in a similar manner since the deflection of x- and y-axis approximately occur at the same position. The sensor was adjusted that way, that a maximal lateral region can be covered. Figure 3 shows that measuring values can be obtained over a range of about $150\,mm$.

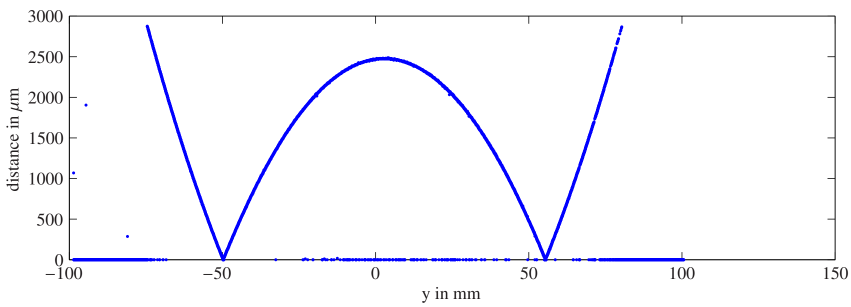

Fig. 3. Scan along the y-axis of the build platform.

At higher angles some of the samples are lost because of the reflective surface. The range obviously depends on the surface properties of the topography observed. Noticeable is the turn over of the signal. This is caused by the characteristic design of the sensor. If no additional measures are taken as incorporating the x-y-scan-coordinates into account, the ambiguity of the measurement value can still be avoided by reducing the used lateral sensor range to 100 *mm*.

5.2. Compensation of surface distortion

In order to examine extrema of profiles, the distortion of the surface has to be taken into account. One way to solve that problem could be the use or reference scans. Figure 4a shows an original scan of an 2-Euro cent coin. A reference scan of an ideal plane is used in this experiment to correct the first scan (4b). The distance between the sampling points is 20 μm. In both measurements blue spots can be observed. These are samples where the sensor was not able to detect a surface, thus resulting in zero values. This happens for example at steps in the surface. For compensation of the original surface the reference is subtracted. Since the reference scan has zero values as well a direct computation would reduce the amount of useful samples. To avoid this and interpolation of the reference scan is used to obtain a complete reference surface. As an initial attempt a polynomial interpolation is done using *MATLAB's Curve Fitting Toolbox^{TM}*. Figure 4c shows the difference of the original measurement compensated by a *'poly55'* fit of the reference scan. Values below 1350 μm have been excluded.

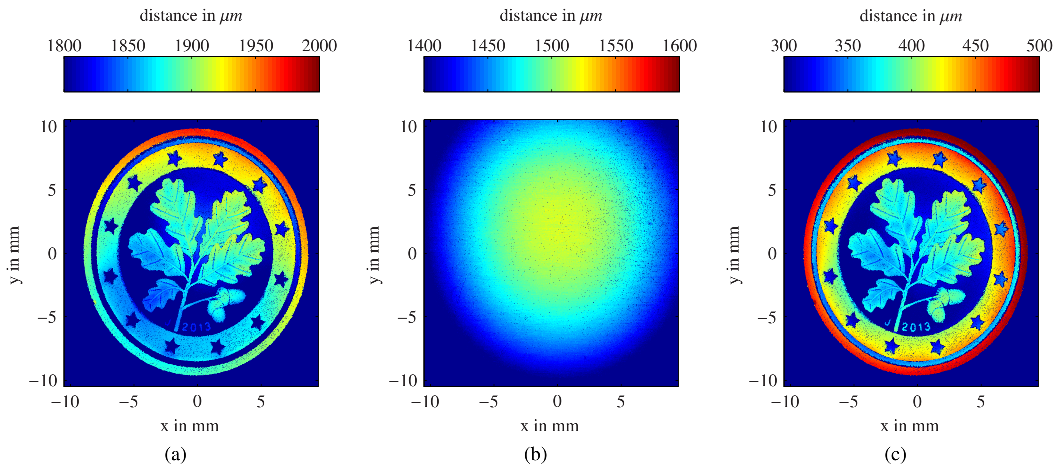

Fig. 4. (a) Original scan of a 2-Euro coin, (b) interpolated reference surface and (c) compensated topography.

5.3. Characterization of melted surfaces

As described in section 4.2 measurements of core regions could be used to derive indexes that characterize the homogeneity of the surface. Theses indexes could also be used for automated parameter studies described in 4.4. To find out which indexes are related to the surface quality two different surfaces are examined: a steel powder layer of approximately 50 μm and a surface with characteristic SLM scan patterns. An area of 3 *mm* times 3 *mm* is captured with a grid pattern of 4 μm sample distance. Figure 5a and 5b show the examined surfaces with the covered area highlighted by the light source that is integrated in the sensor. To achieve an accurate rectangular topology scan of the surfaces the pixel mode of *SCANLABs RTC5* control board is used. Line after line the region of interest is being scanned at nearly constant speed. At defined pixel positions pulses are generated. The pulses are used to trigger the optical sensor. The maximum pixel frequency must not exceed the maximum sampling frequency of the *PRECITEC* sensor of 70 *kHz*. The process PC is able to relate the surface information gathered by the sensor to the trajectory of the scanner. In this experiment the orientation of the scan is directed perpendicular to the melt tracks. That way profiles along and perpendicular to the melt tracks can be analyzed without taking the difference between processing and measuring directions into account during data processing. Figure 5c shows the scan result of the powder surface, figure 5d the result of the melted surface. Both scans have been performed with a pixel distance of $10\,\mu m$. The value has been chosen with respect to the expected particle size of several ten micrometer and expected hatch distances of about $120\,\mu m$.

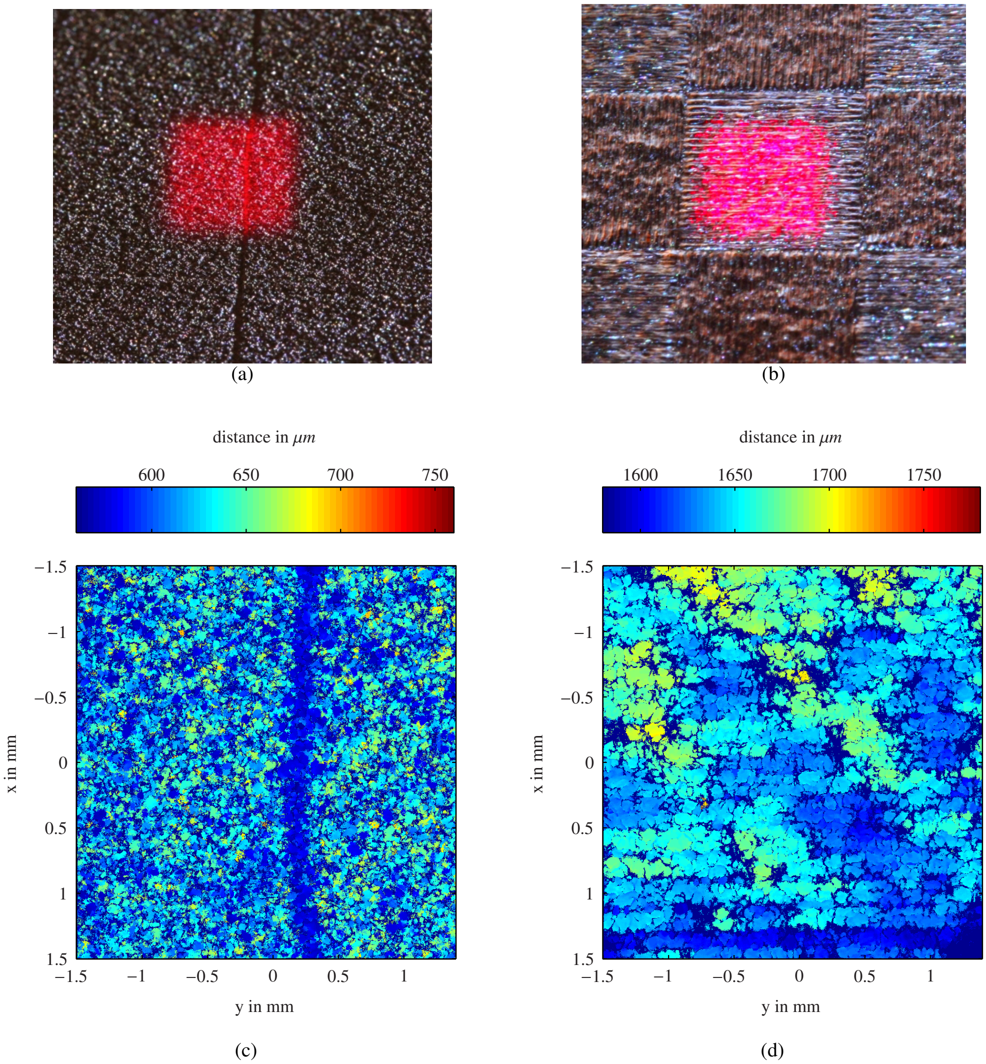

Fig. 5. Surface area cover on (a) powder material and (b) a SLM structure. Resulting profile scans of (c) powder material and (d) the SLM structure.

The profile scan of the powder material in figure 5c shows a defect of approximately $50\,\mu m$ depth that is oriented along the y-direction. Single powder particle of $20\,\mu m - 40\,\mu m$ can be identified. The structures observed in figure 5d are larger. Stripes of $100\,\mu m$ are directed along the x-axis and are assumed to represent the melt tracks. There are differences in height of more than $50\,\mu m$ that exceed typical layer thicknesses. Typical properties of the most different surfaces in SLM seem to be detectable. To be able to use this information for process diagnostics indexes need to be developed that correlate with the quality of the surface. One approach could be the shape of the frequency distribution of a sample set. For the surfaces captured in this work a bimodal distribution has been observed which could originate from the powder surface and the material surface below. Another approach is a cross correlation of line scans perpendicular to the weld tracks. Line scans of randomly distributed powder particles would not show any connection whereas to line scans of SLM surfaces are expected to be very similar. A third way to characterize the quality of SLM surfaces could be the examination of the frequency domain. The hatching of core regions lead to a periodical pattern. Certain sharp peaks might appear for high quality SLM surfaces. Key indexes provided by the *EN ISO 25178* for geometric product specifications could also correlate to the specific surfaces encountered in SLM and help to document and control the production process.

6. Conclusion

In this work the application of a novel optical sensor concept for selective laser melting has been discussed. Several possible measuring tasks along the production process have been described and the relation to part defects been highlighted. The sensor concept has the potential to detect and document defects during the production for every single layer. The measuring range of the current development stage has been experimentally determined. The first experimental results show that topographies captured with the sensor can be distinguished between powder and SLM structures. Possible ways to qualify the layer surfaces have been proposed and will be tested in future works. Generally the low coherence interferometry promises to be a suitable tool for a layer based quality assurance for the selective laser melting technology.

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