Error Detection in Laser Beam Melting Systems by High Resolution Imaging

Kleszczynski, Stefan and zur Jacobsmühlen, Joschka and Sehrt, Jan T. and Witt, Gerd

Institute of Imaging and Computer Vision
RWTH Aachen University, 52056 Aachen, Germany
tel: +49 241 80 27860, fax: +49 241 80 22200
web: www.lfb.rwth-aachen.de

in: Proceedings of the Twenty Third Annual International Solid Freeform Fabrication Symposium. See also BibTeX entry below.

BibTeX:

```
@inproceedings{JAC12a,
  author = {Kleszczynski, Stefan and zur Jacobsm\"{u}hlen, Joschka and Sehrt, Jan T. and Witt, Gerd},
  title = {Error Detection in Laser Beam Melting Systems by High Resolution Imaging},
  booktitle = {Proceedings of the Twenty Third Annual International Solid Freeform Fabrication Symposium},
  year = {2012},
  month = {08}
}
```

ERROR DETECTION IN LASER BEAM MELTING SYSTEMS BY HIGH RESOLUTION IMAGING

S. Kleszczynski*, J. zur Jacobsmühlen†, J. T. Sehrt* and G. Witt*

*Institute for Product Engineering, University of Duisburg-Essen, Germany
†Institute of Imaging and Computer Vision, RWTH Aachen University, Germany

Abstract

Laser Beam Melting as a member of Additive Manufacturing processes allows the fabrication of three-dimensional metallic parts with almost unlimited geometrical complexity and very good mechanical properties. However, its potential in areas of application such as aerospace or medicine has not yet been exploited due to the lack of process stability and quality management. For that reason samples with pre-defined process irregularities are built and the resulting errors are detected using high-resolution imaging. This paper presents an overview of typical process errors and proposes a catalog of measures to reduce process breakdowns. Based on this systematical summary a future contribution to quality assurance and process documentation is aspired.

1. Introduction

Layer-wise creation of solid bodies by joining formless material is the main feature of Additive Manufacturing (AM) technologies. Depending on the different kinds of processes the basic material used could be a powder, a viscous liquid or a solid material. The geometrical data of each layer is gained by slicing digital 3D-models in the suitable thickness. By means of the layer-wise production principle very complex parts can be produced, which may not be manufacturable with other processes. Another benefit of AM technologies is the direct and tool-free generation of parts from CAD data. Today these characteristics of AM technologies are used for many applications including product development and production of individual parts [1], [2], [3].

In the 90ies most applications of AM technologies were found within the domain of Rapid Prototyping, which is until today often confused with AM technologies in general. Beneath this possible field of application the use of AM technologies for so called Rapid Manufacturing or Direct Digital Manufacturing increasingly gains importance [3]. With the development of production techniques for high density metal parts from one-component metallic powders in 1999 [4], a trend of producing individual metal parts for mass customization started. Beam Melting is a neutral term for this special AM technology and was established in the German VDI guideline 3404 [5]. Other terms are Direct Metal Laser-Sintering (DMLS), Selective Laser Melting (SLM), LaserCUSING® or Electron Beam Melting (EBM) which are often related to a specific machine manufacturer. The beam source may be a laser or an electron beam. For this paper only Laser Beam Melting systems are taken into consideration. In the Laser Beam Melting process parts are created through a periodic sequence of powder deposition, layer creation and lowering of the building platform for the next powder deposition as shown in **Fig. 1**. Due to very high cooling rates during the melting and solidification, residual stresses induce curling effects of created layers. To avoid collisions of the recoating mechanism and these curled part areas so-called support structures are necessary. The powder material used in the process can be reused for further processes. Sieving the used powder prevents large particles, welding spatters or other impurities from influencing the powder quality. For creation of layers a beam source melts the powder locally according to the layer specific scanning pattern. The compound of layers and beam paths occurs due to the solidification of the molten discrete areas. Typical applications for Laser Beam Melting can be found in the domain of medical implants, FEM optimized lightweight parts or tool inserts with contoured cooling channels [3]. In spite of its potential a breakthrough of the technology has not yet occurred in many fields of application. One of the main reasons is the lack of process stability and quality management. Especially in areas of high safety requirements like medical engineering and aerospace, customers and users of AM technologies need proof of the accuracy of produced parts. To overcome this barrier it is necessary to find suitable answers to some key questions concerning process stability and quality assurance: which kinds of errors can appear in Laser Beam Melting? What is considered a critical process error? How can these critical errors be detected? And which measures can be taken for debugging?

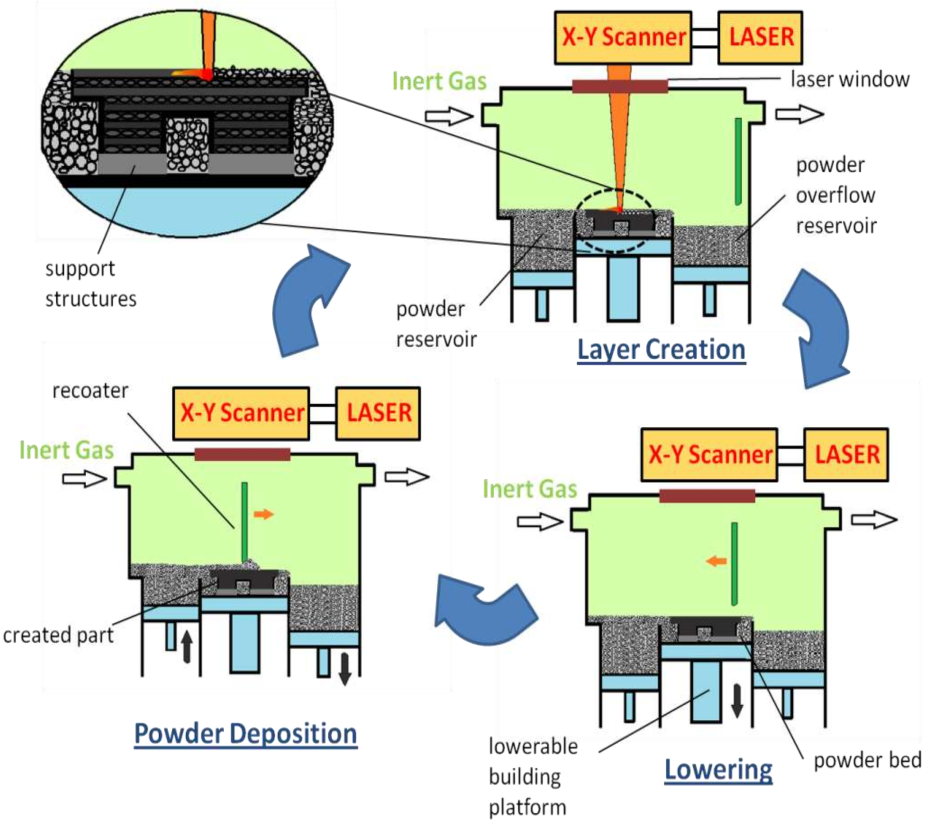


Fig. 1: Schematic representation of Laser Beam Melting.

To find answers to these key questions, we provide a systematic overview of possible errors within the field of Laser Beam Melting. In a second step, errors from each category are detected in sample build processes using high resolution imaging. Upon these results possible measures for debugging during the Laser Beam Melting process are discussed.

2. State of the Art

Laser Welding as an established manufacturing process shows a few similarities to Laser Beam Melting. One thing both processes have in common is the importance of a defined heat input. For example, too much laser power will eventually cause hot cracks, too little energy might be responsible for poor composite weldseams. In the area of Laser Welding, these and other process errors are known and have already been categorized in international standards like DIN EN ISO 13919-1 [6].

On the basis of this knowledge several approaches for optical process control systems were developed and commercialized. Most of them are based on cameras or photodiodes and use a beam splitter which enables a coaxial view through the laser beam. By imaging the emitted light from the welding interaction region in this manner, closed-loop process control systems are able to regulate process characteristics such as laser power, welding speed or filler wire feed rate [7], [8].

In the area of Laser Beam Melting these principles were adopted for the development of first approaches to process monitoring. Kruth et al. used a combination of a visual inspection CCD camera system and a melt pool monitoring system [9], [10]. The CCD camera system inspects the deposition of powder – due to wear and local damage the powder recoating system could cause irregularities in the powder surface deposited on the molten parts. These irregularities remain on the part surface after layer creation and induce high surface roughness. To detect this process error a light source has been mounted in front of the process chamber to illuminate the horizontal lines caused by the damaged powder recoating system. The perspective error caused by an angular camera position has been corrected by means of calibration algorithms. An analysis of grey values was used for the detection of powder bed irregularities. The melt pool monitoring system uses a CMOS camera and a photodiode. By means of a semi-reflective mirror the laser light is deflected towards a beam splitter, which separates the melt pool radiation towards the photodiode and the CMOS-camera. This setup enables coaxial image acquisition through the laser beam. Melt pool dimensions are measured by means of the CMOS camera. The photodiode detects the mean radiation, which is emitted from the melt pool. The possible resolving power reached by this setup is about 10 µm per pixel [10]. Similarly to Laser Welding it is possible to control process parameters like laser output power with this approach. This is useful for areas with varying thermal conductivity like overhanging structures. [11]

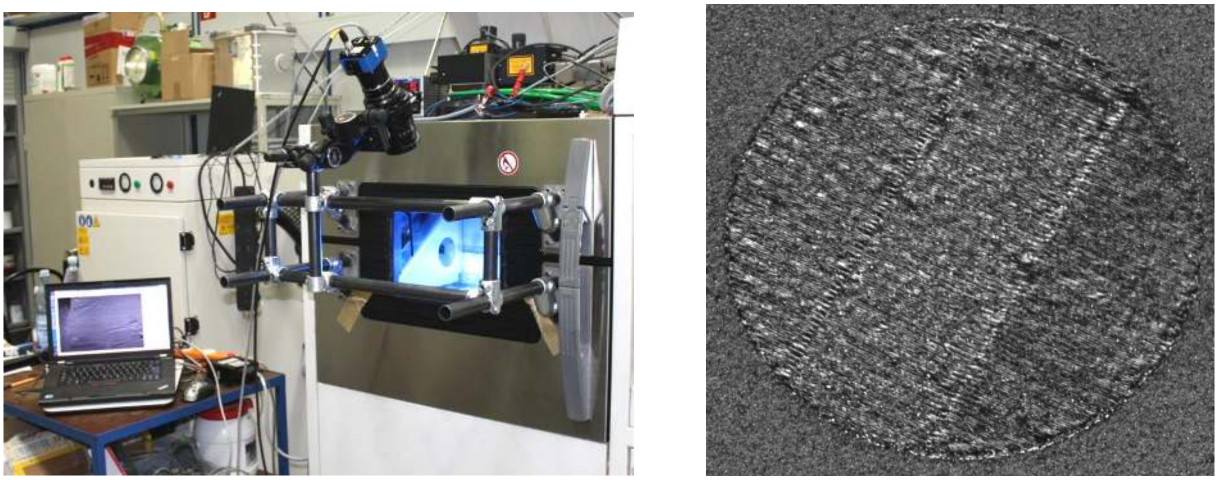
Lott et al. expanded Kruth's approach by imaging melt pool dynamics at higher scanning velocities by means of an additional laser illumination. The achieved resolution of this system was about 12 µm per pixel [12]. Another approach has been given by Pavlov et al. [13]. Here, a bi-color pyrometer system was installed coaxially to the laser beam. For the analysis of thermal processes the parameters of hatch distance and powder thickness were varied.

All mentioned approaches are using complex process monitoring systems which require a modification of the optical components of Laser Beam Melting systems. The complexity of these modifications presents a major drawback of these systems. Additionally, the field of view of all systems is limited to the current melt pool and its direct surroundings. The cooled down surface is not inspected, leaving the process result unsupervised. Performance of the described monitoring systems has been measured for selected process errors, only. A comprehensive documentation of process errors detected by the different approaches has not been given yet. Furthermore some concepts are patented or licensed which makes it difficult to use them in different Laser Beam Melting systems.

For some types of process errors an in situ detection and documentation by means of a high resolution imaging system provides some advantages. We therefore present in this paper an alternative approach to error detection, which is system-independent and easy to implement.

3. Experimental Setup

All studies described in this paper were made using an EOSINT M 270 Laser Beam Melting System from EOS GmbH. The powder material used was EOS NickelAlloy IN625. To provoke different kinds of process errors, parameters were varied in a wide field around the recommended standard. Process stability was investigated by building test bodies with critical geometrical features. Additionally, some types of errors were provoked by manipulating actors and optical components or using different powder qualities. For the latter waste powder was collected after sieving which contains larger particles.



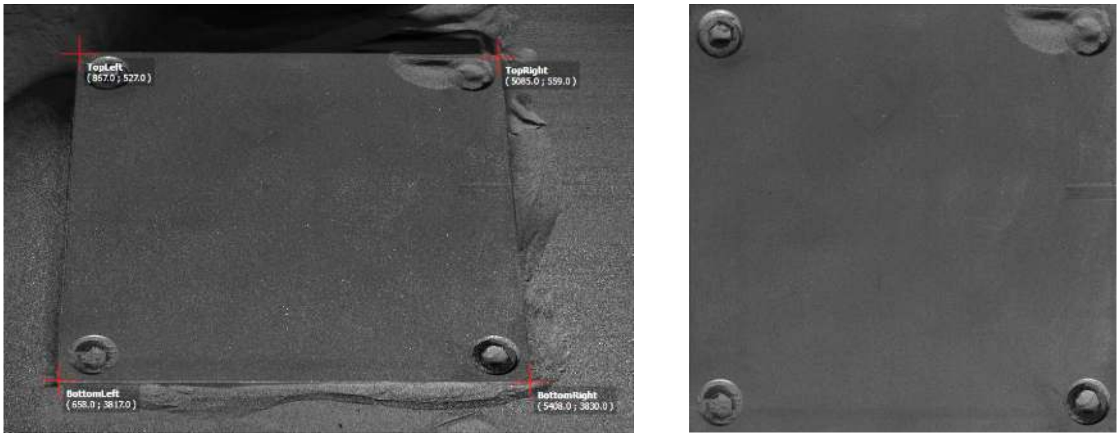
a) **b)**

Fig. 2: a) Setup of the CCD camera system in front of machine window. **b)** Example image.

For visual detection and analysis of errors a monochrome CCD camera system was used. The camera (SVCam-hr29050, SVS-VISTEK GmbH) was mounted in front of the machine window on the outside and captured images of the build platform from an observation angle **(Fig. 2a**). A tilt and shift lens (Hartblei Macro 4/120 TS Superrotator) helped to reduce perspective distortion by shifting the camera back and allowed placing the focal plane on the build platform without stopping down using its tilt ability. A 20 mm extension tube reduces the minimum object distance of the lens. The camera uses a 36 by 24 mm Kodak 29 megapixel sensor (6576 by 4384 pixels, pixel size 5.5 µm by 5.5 µm).

We built all test bodies on a small building platform (100 mm by 100 mm) to evaluate the capabilities of our system at highest possible resolution. Later, the system can be extended to monitor the entire building platform (250 mm by 250 mm) at the cost of a reduction in spatial resolution.

Resolving power of this setup was measured experimentally for a field of view of 130 mm by 114 mm with maximum lens tilt (8 °) and shift (10 mm) to minimize perspective distortion for a position similar to the final setup in front of the machine window. We used an USAF 1951 target and a microscope calibration slide with four circles on it (diameters: 1.5, 0.6, 0.15 and 0.07 mm) and acquired five images of each target by placing it in the center and at all four corners of the field of view. Perspective distortion was corrected by transforming the corners of the work piece carrier to a square in the image using four point homography estimation and warping with bicubic interpolation, resulting in an orthogonal view of the test target with a resolution of about 19 µm/pixel (see **Fig. 3**). The camera system is able to resolve two black lines on white background (40µm wide, 40 µm apart) from a distance of 50 cm. All circles on the microscope slide were detected and confirmed the pixel size. As can be seen from **Fig. 2b** this system enables us to inspect the part surface at bead level.



a) b)

Fig. 3: Example of perspective correction. (a) Building platform with corner markers and some powder in top right corner. (b) Corrected image of work piece carrier provides an orthogonal view of the build platform. Note: images intensities have been rescaled for visualization.

Images presented in this paper were corrected using the same method. The edge length of the target image can be chosen arbitrarily; we used the minimum edge length of the distorted quadrilateral image to reduce the number of interpolated pixels, resulting in an image resolution of 4234 x 4234 pixels (~24 µm/pixel). The slightly larger pixel size in the object plane compared to the resolving power measurement is due to the larger field of view in the machine.

For optimum image quality adequate lighting is required which must provide homogenous lighting for the mirror-like metallic weld bead structures to minimize specular reflections which would saturate the camera's CCD sensor. It was found that diffuse lighting with a light source placed close to the working surface and opposite to the camera produces the best quality for surface images. As the contrast of adjacent beads in the camera image depends highly on the shadow which is casted by each bead, the light source should always be perpendicular to the current bead orientation.

In the machine, the powder blade movement prohibits the placement of any lighting component on the back of the machine. Therefore we realized diffuse lighting using matt reflectors on the back of the machine and powder blade (see **Fig. 4**) which are illuminated by two directed light sources from the front and right, respectively. Optimum lighting for alternating scan pattern is provided by two orthogonal light sources, one of which is selected depending on the current bead angle. Dark field illumination, which uses lighting parallel to the building plane to highlight surface disturbances, is applied separately. For each layer we acquire at least two images: one after powder deposition and one after laser beam melting. For lighting evaluation and better illustration we took images of typical errors with all possible lightings.

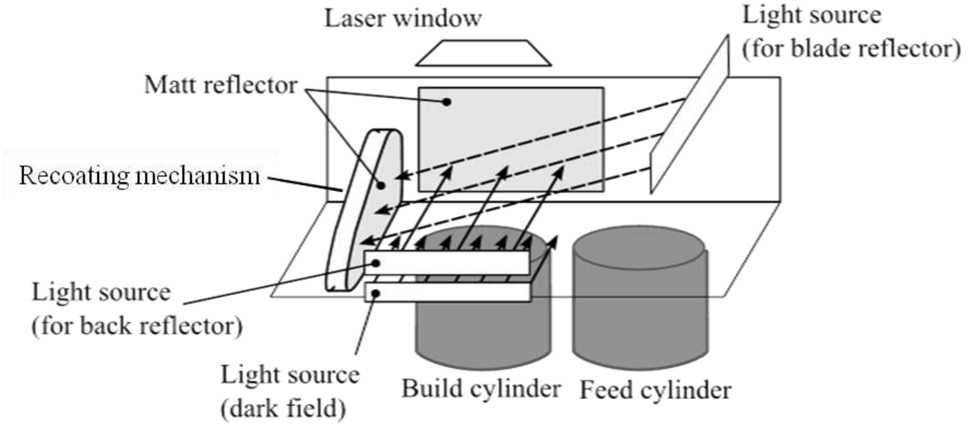


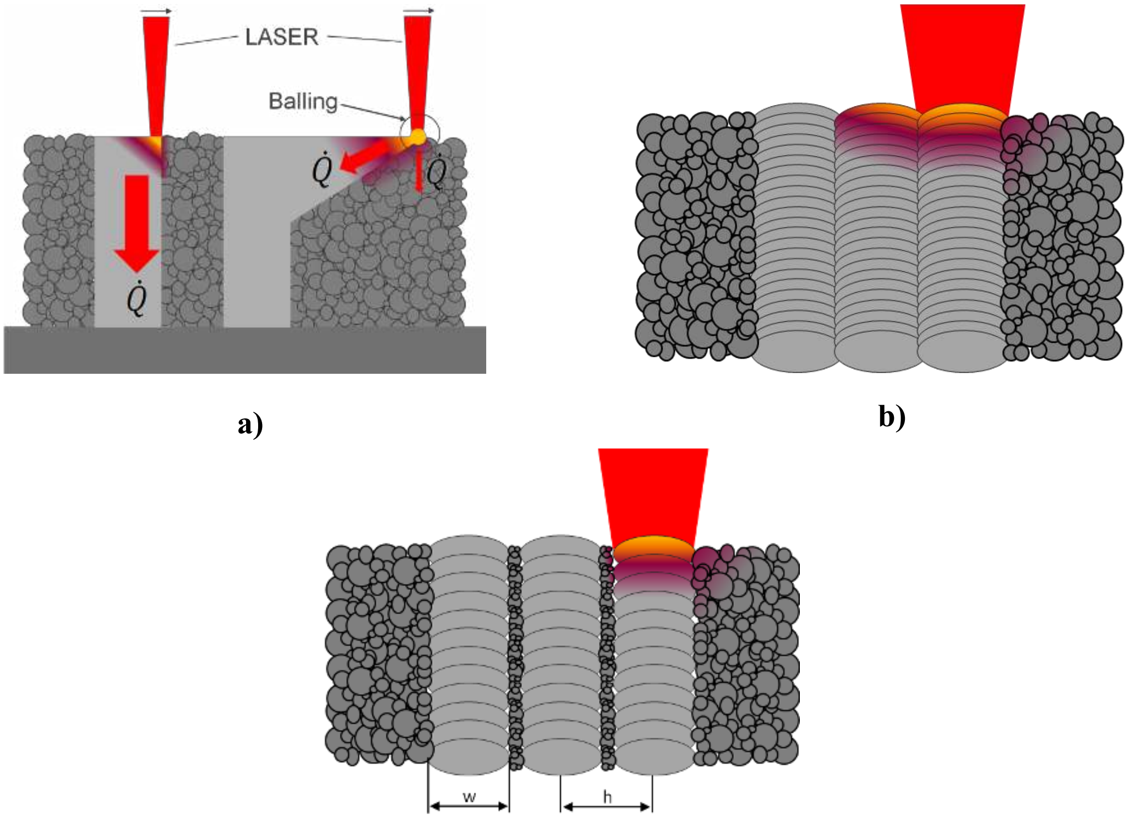
Fig. 4: Lighting setup for surface inspection and detection of elevated areas. Three light sources are used independently based on the current detection scheme. Contrast between adjacent beads is enhanced by illumination from the right side for bead angles from 45 ° to 135 ° and illumination from the front for angles from 0 ° to 45 ° and 135 ° to 180 °. Reflectors enable diffuse lighting on the work plane; dark field lighting uses parallel lighting to highlight embossments, it is used separately from the other two lighting sources.

4. Results and Discussion

Process Errors in Laser Beam Melting

Before presenting images of typical process errors, the kinds of errors which can occur in the Laser Beam Melting process have to be defined. The following deliberations assume worst case scenarios in which errors are caused by human or technical failures. Basically the occurrence of these errors can affect process stability or part quality.

Process stability is primarily endangered by collisions of the recoater mechanism and curled areas. As described in the first section of this paper, very high cooling rates during melting and solidification are causing residual stresses which induces plastic deformations within the created layers. If the necessary support structures cannot compensate these deformations, a collision with the recoater mechanism stops the running process. Depending on the intensity of the occurred superelevation, support structures or parts are broken and lose their connection to the building platform. Critical geometric features can be another reason for local superelevations. Depending on the used material and process parameters there is a critical angle for overhanging structures up to which support structures are necessary. As a rough guide value 45° overhang can be considered as critical threshold. Especially for the creation of very complex parts a compromise between stable support connections and easy support removal has to be found. Some geometrical features are even intended as functional areas within the created part and should therefore exhibit a certain surface quality which is influenced negatively by support connection. Beside the avoidance of curling effects, support structures are important for heat conduction, due to the fact that the conductivity of metal powders is about three orders of magnitude lower than that of solid metal [4]. If the heat induced by the laser beam is not conducted into the building platform, so called balling effects appear (**Fig. 5a**). Here, surface tensions of the viscous melt cause spherical areas within the part after solidification. The same problem occurs when too much heat in proportion to the surface area is conducted into the part. As for critical overhanging structures this heat accumulation induces balling effects. Some Laser Beam Melting Systems use a stiff ceramic or metal blade for the recoating process. Due to the inflexible blade, elevated or curled part areas are causing a jam during the recoating process. Other Systems are using flexible silicon blades for recoating. With this setup jams can be mostly avoided, but there will be a higher wear of the flexible blade, which finally leads to uneven powder layers after powder recoating. Another source of error can be found in the connection of supports to the part. There are many support parameters which influence thickness, connection or removability, so that finding suitable parameters for support structures often depends on the specific experience of the technology users. In consequence, the connection of supports to the built part can be referred to as a critical process phase, in which an insufficient compound could cause superelevations or a detachment of the built part. In both cases the process is demolished and has to be stopped. Furthermore process stability can be endangered by insufficient powder supply. This could be caused by a defective actuator in the powder reservoir platform mechanism or by powder reservoir exhaustion. Sensing devices usually notice when the powder stock is exhausted, but in worst case scenario a technical defect could prevent the running process from being stopped to refill the powder reservoir. Another reason for insufficient powder supply could be that the powder has not been compressed properly. Depending on the particle size distribution cavities could occur which collapse when the powder reservoir moves. As a consequence the powder level could not be sufficient for powder deposition. If there is no powder deposited on the created layers the laser beam will re-melt the solidified areas. Due to the repeated heat input by means of a defocused laser beam and the missing powder supply the so created parts cannot be completed.



a)

b)

c)

Fig. 5: a) Balling formation due to insufficient heat conduction caused by overhanging structures, **b)** good composite weldseams, **c)** poor composite weldseams by a wrong ratio of hatch distance *h* and width *w* combined with a high scanning velocity

Part quality is mainly measured by mechanical properties, surface roughness and dimensional accuracy. Depending on the utilized material and the heat input per second, hot cracks could eventually harm product quality. The formation of cracks is mainly the result of high cooling rates during the Laser Beam Melting process. Brittle materials are particularly susceptible to this error type. Most materials available for Laser Beam Melting process show a good weldability and are assigned to ductile metal alloys. However, powder contaminations or different concentration of elements within the powder particles could cause these defects. To ensure proper mechanical properties of the created parts, the creation of good composite weldseams is essential. For this purpose a defined ratio between width and distance of melt traces has to be achieved (**Fig. 5b**). The width of melt traces depends on laser beam diameter, laser scanning velocity, powder layer thickness and laser power. If the distance of melt traces – so called hatch distance – is too large, the compound of the respective melt traces will be deranged, which will finally cause porosities, resulting in poorer mechanical properties. A sudden decrease in laser power, e.g. caused by laser window pollution due to condensate deposits, a technical defect in the build platform actuator or an uneven platform resulting in a thicker powder layer at constant laser power leads to the same error type (**Fig. 5c**). Laser scanning velocity influences how much energy per second is conducted into the powder layer. A technical defect in the scanning system could therefore cause superelevations if scanning speed is too low, or poor composite weldseams if scanning speed is too high.

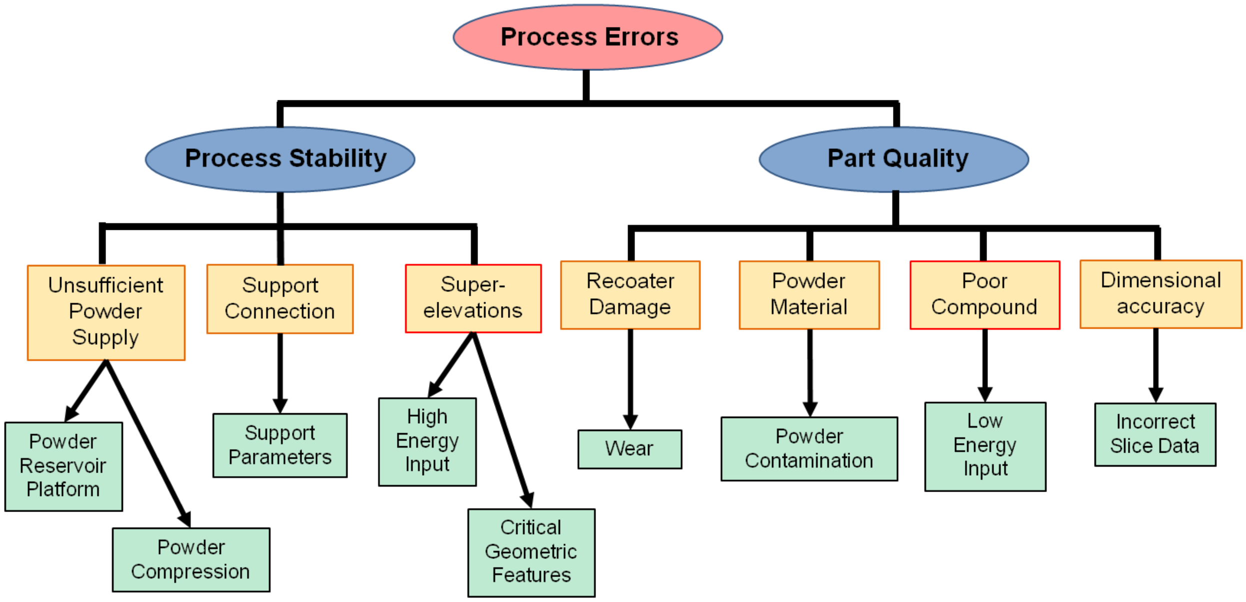


Fig. 6: Typical Process Errors in Laser Beam Melting categorized by influence, type and cause.

Another main influence on product quality is the surface roughness. It is known that due to powder adhesion on part edges the measured surface roughness is larger in these areas. Better surface qualities can be achieved on surfaces parallel to the building platform. If there are disturbances in these layers, the surface quality could however be influenced negatively. Possible disturbances can occur due to a damaged recoater blade, caused by wear or superelevated areas, or contamination of the deposited powder. In case of a damaged recoater blade horizontal stripes are visible resulting in a locally thicker powder layer, which finally leads to unevenness in the created layer. A contamination of powder could be caused by non-metallic or coarse particles. Due to these foreign particles the necessary heat of fusion is locally different and therefore causes irregularities after solidification. Dimensional accuracy is another quality feature, which is influenced negatively by material shrinkage after solidification and incorrect geometrical slice data. **Fig. 6** presents a systematic summary of all mentioned process errors.

Error Detection by High Resolution Imaging

According to the subdivision of process errors this section presents different types of errors in Laser Beam Melting using the described high resolution imaging system. In a first building test, process stability was examined by building different sample geometries with critical geometric features and critical support connection. Additionally three cylindrical geometries were built for determination of the impact of contaminated powder.

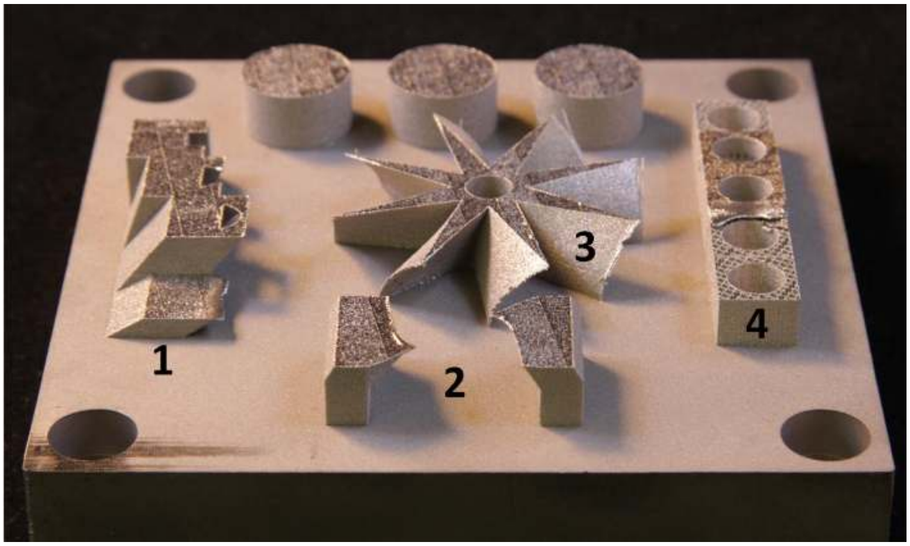


Fig. 7: Test samples built for examination of critical geometrical features and powder contamination

As can be seen in **Fig. 7** three test geometries have critical overhanging angles and were not connected to support structures. Part one and part two were placed parallel to the recoating mechanism which is unfavorable, due to the fact that in case of superelevation there is a large contact area between recoater and elevated part areas. This might cause a jam of the recoating mechanism. Part one furthermore features holes on the right side, which are critical when they are growing together. Part two features a critical overhanging area without support structures. Part three was inspired by turbine impellers, which feature overhanging blades. Support structures in these areas are difficult to remove. In consequence these parts are often built without any support structures which endangers process stability.

Fig. 8a shows an image of this first test process taken in a z-built position of 5 mm after layer creation. **Fig. 8b** shows the same setup after powder recoating. As can be seen some areas of part one to three are superelevated and had contact to the recoating mechanism. **Fig. 8c** shows a detail of **Fig. 8b**. Depending on part geometry the superelevated areas will rise after each created layer. Furthermore there are horizontal lines visible in **Fig. 8c** which were caused by a damaged recoater blade. Part four in **Fig. 7** features supported overhanging surfaces in different levels. The influence of different support connection parameters was investigated by this test sample. To achieve poor support the stability laser power used for support creation was decreased. After recoating some support particles were torn away by the recoater blade. These particles are also visible in **Fig. 8d.** The marked area in **Fig. 8d** shows the first part layer created on the poor support structures. **Fig. 8e** shows a magnified view of this area. Support connection was not stable enough to avoid curling effects of the created layer. With the next recoating procedure the recoater would tear off the created layer or even cause a jam. Finally **Fig. 8f** shows a magnified image of one cylindrical test sample after being exposed with contaminated powder. Comparing this image with **Fig. 8e** shows that the powder particles seem to be much darker and coarser than those of **Fig. 8e** (note that all images presented have been brightened for printing in the same manner). The solidified area in **Fig. 8f** shows a much more irregular surface. Melt traces are much more difficult to observe.

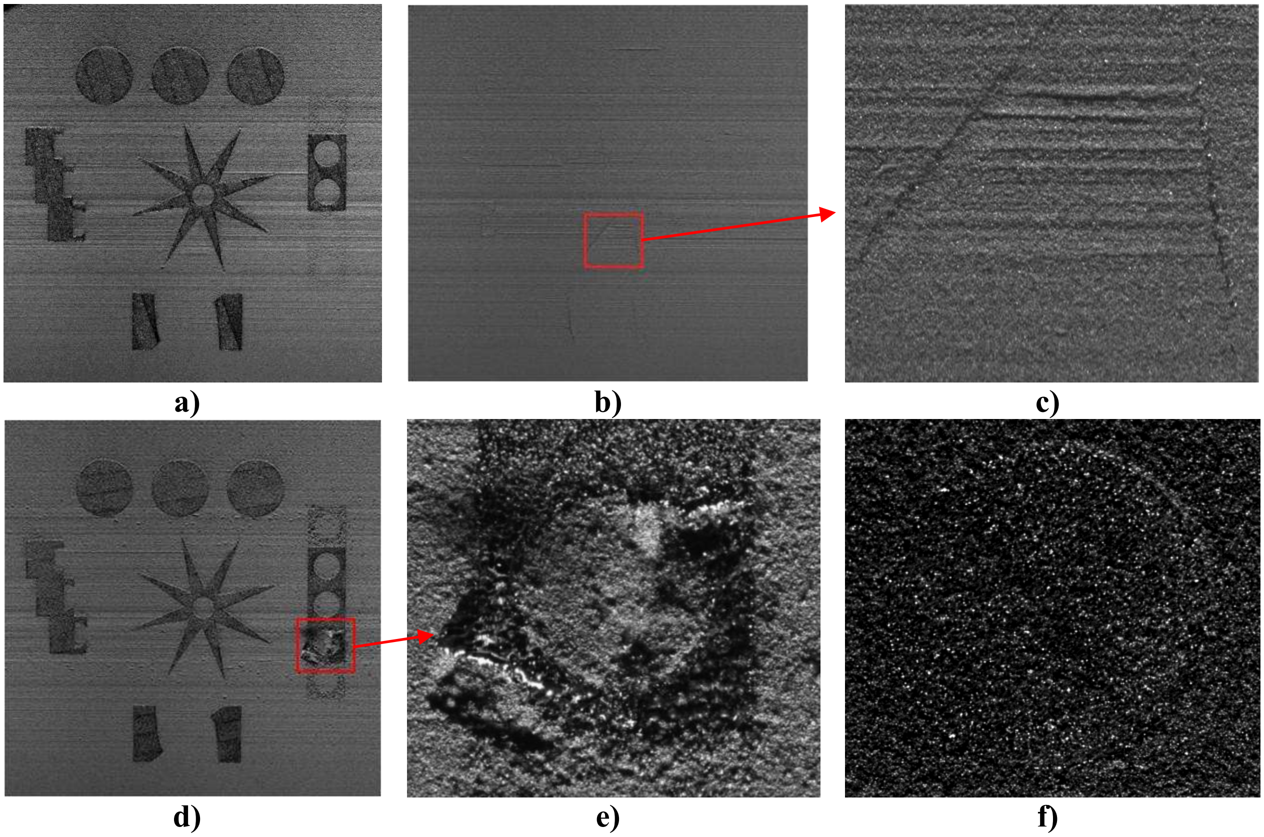


Fig. 8: Various types of errors influencing process stability. See text for full description. All pictures were taken with the described high resolution imaging system. Note: image intensities have been rescaled for visualization purposes.

In a second built process nine cylindrical test sample were built as shown in **Fig. 9b**. Herein the influence of energy input was examined. The three cylindrical test samples on the left side were assigned with process parameters that cause a low energy input. In detail the upper test sample was built using a laser power decreased by approximately 40 %. The middle test sample was built with a hatch distance increased by approximately 30 %. Finally the lower test sample was built using a scanning velocity increased by 40 %. According to this, the test samples on the right side were built using high energy input parameters. The three samples in the middle were build using optimized parameters. After taking images as a reference, the laser beam diameter was enlarged for these samples. Through this energy input was decreased. **Fig. 9a** shows the test sample with enlarged hatch distance. The part exhibits a rough surface and irregularities. According to the remarks at the beginning of this section the image shows a poor compound of melt traces. It is remarkable that the upper and the lower samples nearly show the same appearance. **Fig. 9c** shows a representative sample with high energy input. The sample shows a smooth surface with superelevated areas at the sample edges. The superelevation of the edge regions can be better seen after powder recoating in **Fig. 9f**. Finally **Fig. 9e** shows the surface of a cylindrical sample built with optimized parameters. Herein good composite weldseams are visible. No regions of superelevation can be recognized. After enlarging the laser beam diameter the same sample is again illustrated in **Fig. 9d**. As can be seen the surface is quite similar to those of **Fig. 9a**; it has become more rough and coarse particles are visible due to some reflections at the particle's surface. The same error appearance would occur for increased powder layer thickness.

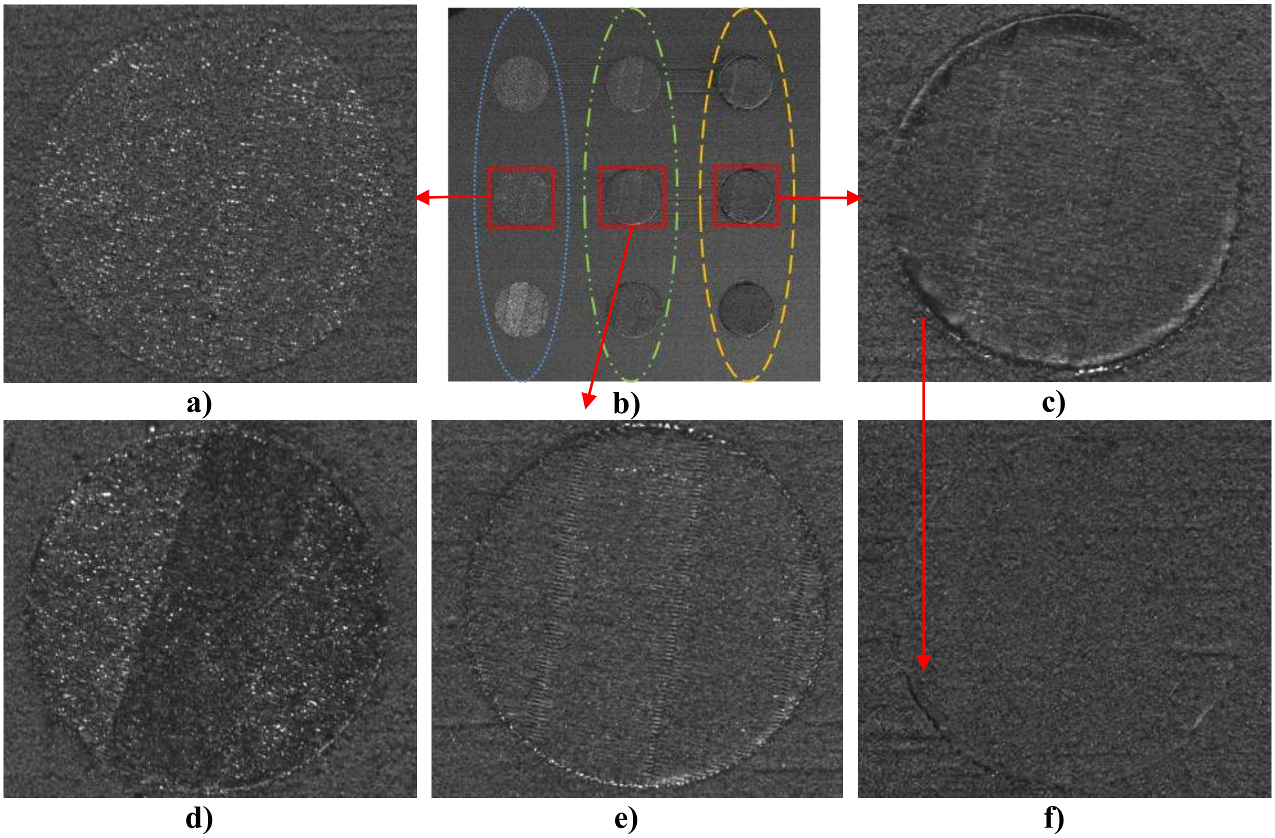


Fig. 9: Various types of errors influencing product quality. See text for full description. All pictures were taken with the described high resolution imaging system. Note: image intensities have been rescaled for visualization purposes.

5. Conclusions

With this paper an alternative approach to error detection in Laser Beam Melting has been given. The used high resolution imaging system is easy to implement and therefore compatible to any existing Laser Beam Melting system. Furthermore the described high resolution imaging system is able to measure geometrical features and could therefore be used for the control of dimensional accuracy. Investigations for this option will be discussed in future publications. According to the systematical subdivision of process errors made in this paper and the documented error types it can be stated that superelevations and poor support connection are the most critical errors in the field of Laser Beam Melting. A possible measure for debugging this type of error could be a reduction of heat input in the affected areas. Hereby process heat can better be conducted through the solidified part areas and might therefore reduce heat accumulation. For this purpose coupling of the process monitoring system and the process control software is necessary. A low energy input could reduce part quality and is therefore undesirable in fields of applications with high safety requirements. Checking machine components and process parameters after the detection of low energy input errors can be stated as a necessary measure. If this error is detected in an early state, repeated exposure of the low energy input areas could be a measure for debugging this type of error. Powder contaminations and a damage of the recoating mechanism can be fixed easily after detection and are therefore regarded as less critical types of errors. The detailed effects of different types of errors on mechanical properties and semi-automated image analysis will be discussed in following publications.

6. Acknowledgment

The authors would like to thank the AiF association of industrial research unions “Otto von Guericke” e.V. (Berlin) for funding the research within the IGF research project “Entwicklung einer bildgestützten, anlagenunabhängigen Überwachung von generativen Strahlschmelzprozessen - BIGS” (IGF-Vorhaben Nr. 17042 N).

7. References

[1] Gebhardt, A.
Generative Fertigungsverfahren - Rapid Prototyping - Rapid Tooling - Rapid Manufacturing. München : Carl Hanser Verlag, 2007. ISBN: 978-3-446-22666-1.

[2] Zäh, M. F.
Wirtschaftliche Fertigung mit Rapid-Technologien - Anwenderleitfaden zur Auswahl geeigneter Verfahren. München Wien: Carl Hanser Verlag, 2006. ISBN: 978-3-446-22854-2.

[3] Gibson, I.; Rosen, D. W.; Stucker, B.
Additive Manufacturing Technologies - Rapid Prototyping to Direct Digital Manufacturing.
Springer New York Heidelberg. ISBN 978-1-4419-1119-3

[4] Meiners, W.
Direktes Selektives Laser Sintern einkomponentiger metallischer Werkstoffe. PhD Thesis, Aachen: Shaker Verlag 1999, ISBN 3-8265-6571-1

[5] N., N.
VDI-Guideline 3404: Additive fabrication - Rapid technologies (rapid prototyping) - Fundamentals, terms and definitions, quality parameter, supply agreements. Berlin: Beuth Verlag, 2009

[6] N., N.
DIN EN ISO 13919-1. Elektronen- und Laserstrahl-Schweißverbindungen - Leitfaden für Bewertungsgruppen für Unregelmäßigkeiten. Berlin: Beuth Verlag, 1996

[7] Bardin, F.; Cobo, A.; et al.

Closed-loop power and focus control of laser welding for full-penetration monitoring. In: APPLIED OPTICS. Vol. 44 (2005). No. 1. pp. 13 - 21

[8] Haran, F.; Hand, D.; Peters, C.; Jones, J.
Focus control system for Laser Welding. In: APPLIED OPTICS. Vol. 36 (1997). No. 21. pp. 5246 - 5251

[9] Craeghs, T.; Clijsters, S.; Yasa, E.; Kruth, J.-P.
Online Quality Control of Selective Laser melting. In Proceedings of the Solid Freeform Fabrication symposium (SFF) 2010. pp. 212 - 226 Austin (Texas - USA), August 2010

[10] Berumen, S., Bechmann, F., Lindner, S., Kruth, J.-P., Craeghs, T.
Quality control of laser- and powder bed-based Additive Manufacturing (AM) technologies. Physics Procedia 5 (2010). pp. 617 - 622. LANE 2010

[11] Kruth, J.-P.; Mercelis, P.; Procedure and apparatus for in-situ monitoring and feedback control of Selective Laser Powder processing. Patent. Pub. No.: US 2009/0206065 A1

[12] Lott, P.; Schleifenbaum, H.; Meiners, W.; Wissenbach, K.; Hinke, C.; Bültmann, J.
Design of an Optical system for the In Situ Process Monitoring of Selective Laser Melting (SLM). Physics Procedia 12 (2011). pp. 683 – 690. LiM 2011

[13] Pavlov, M., Doubenskaia, M., Smurov, I.
Pyrometric analysis of thermal processes in SLM technology. Physics Procedia 5 (2010). LANE 2010