3D ANALYSIS IN LASER BEAM MELTING BASED ON REAL-TIME PROCESS MONITORING

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Abstract

In the course of increasing application of laser beam melting (LBM) technology for series production, LBM process monitoring becomes more and more important for quality control during and after the production process. Especially for safety-relevant parts, such as aircraft and motorsport components or medical implants, process robustness and quality assurance is basic assumption for a wide adoption of LBM technology in these industries. Furthermore, real-time monitoring is fundamental for self-regulating process control of LBM machines. But before that, extensive research on interrelations between sensor signals and process conditions need to be done. In this contribution, newest results on process failure and defect detection using Concept Laser’s coaxial IR camera and photodiode based QM Meltpool 3D are addressed. This systems newest 3D feature, providing a detailed 3D landscape of position-related meltpool characteristics, is compared to CT inspection data. Hence, advantages for part inspection and it’s usage in research are presented.

Introduction

Laser Beam Melting (LBM) is a metal 3D printing technology and also known as LaserCUSING®, Selective Laser Melting (SLM®), Powder Bed Fusion or metal additive manufacturing (AM). After its initial invention in the 1990s, e.g. described in [1], LBM process development and its application in different industrial sectors is gaining in importance [2, 3]. Today, metal 3D printing is still predominantly used for prototype and small series production. First parts, especially from high-tech industries like aviation or medical technology, have been identified for series production using additive manufacturing with technical and/or economic advantage [4-8]. However, regulatory requirements for certification and operation of 3D printing technologies for series production increasingly involve new methods for process and part quality assurance. Due to the large number of influencing factors in LBM [9], the identification of process deviations requires a fundamental process understanding and indicates high requirements for process monitoring tools. According to this, different methods for monitoring systems had been developed in the last years [10]. One promising approach is the optical measurement of the thermal radiation, while melting the metal powder. In this context, Concept Laser GmbH, Germany-based pioneer and one of the world’s leading suppliers of machinery and technology for metal 3D printing, has developed the first position-related, real-time monitoring system for their patented LaserCUSING® process, called QM Meltpool 3D [11, 12]. In Figure 1 the basic principle and appendant hardware of QM Meltpool 3D are shown.

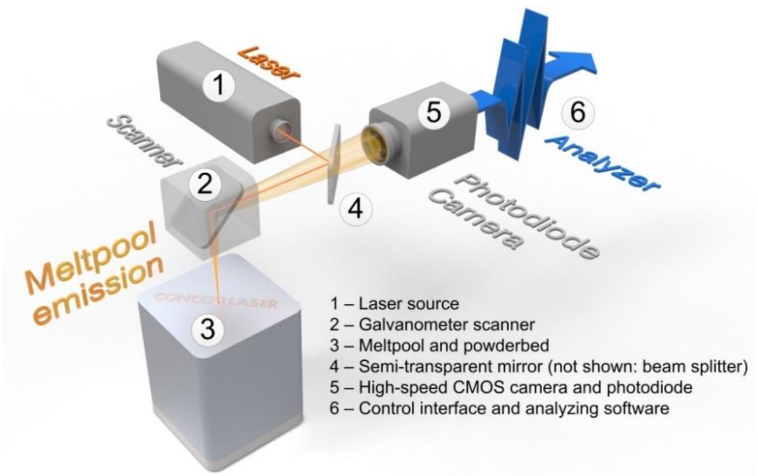

Figure 1. Principle and main components of QM Meltpool 3D system [11].

In QM Meltpool 3D, an infrared high-speed camera and photodiode are installed coaxial in the optical path of the LBM machine. An additional infrared translucent static optical mirror in the optical path between the laser source and the scanning system allows the on axis detection of melt pool emissions. The measuring requirements are high solution and are high sampling rate because of melt pool sizes down to 1/10 mm and laser scan speeds up to 4,000 mm/s. Therefore, an off axis approach monitoring the complete LBM powder bed at once and the melt pool in detail is not feasible.
The above mentioned measuring principle is patented by KU Leuven, Belgium [13] and has been developed to application maturity by Concept Laser GmbH, available as QM Meltpool since 2010 [14, 15]. At this level of development an average melt pool intensity (by photodiode) and melt pool area (by camera) for each layer was measurable. Thus, process deviations, e. g. differences in laser power or powder layer thickness, were detectable. Main deficit of this state is that there was no exact localization and dimension of the melt pool emissions detectable. Thus, it was only possible to identify significant differences between parts of the same geometry, exemplary shown in Figure 2.

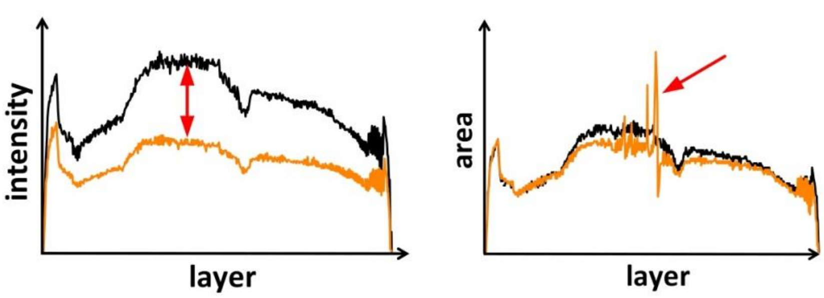

Figure 2. Melt pool intensity for two identical parts manufactured with different laser power (left chart) and modified powder dosing (layer thickness) in the middle layers (right chart).

In the current development stage QM Meltpool, has been enhanced with crucial features that rise process monitoring to an advanced level. This particularly comprises a new control interface and analyzing software, which are able to project each position-related melt pool intensity and size onto the three-dimensional part geometry. Both sensors, camera and photodiode, are capturing with a resolution up to 35 µm and a sampling rate of 15 kHz (camera) and 50 kHz (photodiode) [16]. In process, the highest resolution is depending on the laser scan speed, e. g. 100 µm at 1,500 mm/s and corresponding 200 µm at 3,000 µm [11]. The collected data of melt pool emissions are correlated to the corresponding scanner positions and processed in real-time on an industrial PC (IPC). The QM Meltpool 3D software on the IPC computes a grey scale map as Tagged Image File Format (TIFF). Image computation takes place for every part after each layer during the LaserCUSING® process. In this manner, a stack of image files can be analyzed during or after the manufacturing process. The generated image files can be analyzed within a separate desktop software from Concept Laser (individual images, sequences and comparison of images of different parts) and additionally with any commercial software for computed tomography (CT) data processing in the same way as CT image stacks. Figure 3 demonstrates the progress from QM Meltpool to QM Meltpool 3D, from time-related to spatially resolved data being fully capable for three-dimensional analysis.

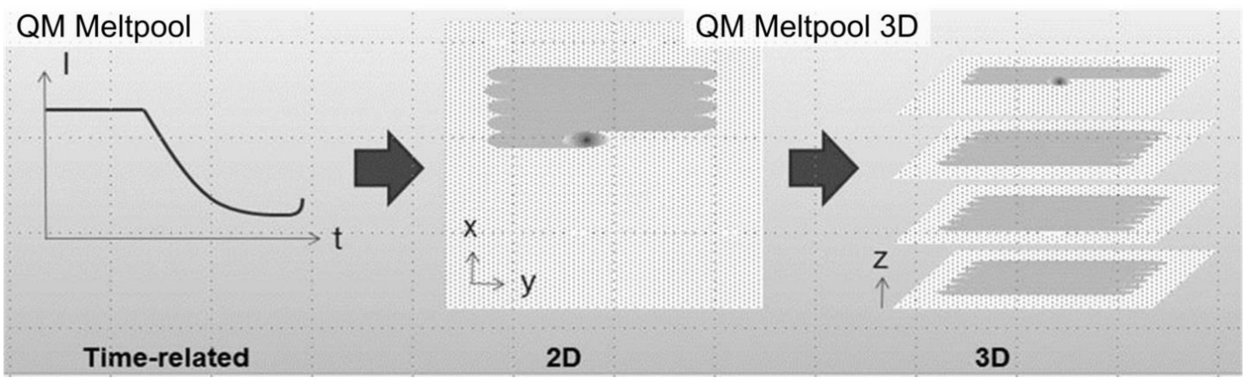

Figure 3. QM Meltpool becomes QM Meltpool 3D [17].

In this article, newest results on process failure and defect detection using QM Meltpool 3D are presented. In the course of this, experimental results and comparisons to CT scans are shown. In conclusion, advantages of QM Meltpool 3D for part inspection and usage in research are discussed. All works presented in this paper were carried out by Fraunhofer IWU in close collaboration with Concept Laser GmbH.

Experimental setup, material and methods

Equipment and material

All LBM specimens presented in this paper were manufactured on a M2 cusing machine (manufacturer: Concept Laser GmbH) at Fraunhofer IWU Dresden. This LaserCUSING® machine is equipped with a 400 W diode-pumped fiber laser (wavelength 1,070 nm), ScanLab hurrySCAN scanning system and QM Meltpool 3D monitoring system. The specimens were manufactured in two different materials – a lightweight aluminum alloy with high thermal conductivity and low absorption rate for the employed laser wavelength and a nickel superalloy with low thermal conductivity and comparably good laser absorption rate, see Table I.

Table I. Materials specifications and default process parameter

Specification / parameter	CL 31AL	CL 100NB
Alloy type	AlSi10Mg	NiCr19NbMo (INCONEL® 718)
Density*	2.68 g/cm³	8.19 g/cm³
Thermal conductivity*	113 W/m·K	11.4 W/m·K
Melting point*	557 - 596 °C	1,260 - 1,336 °C
Laser absorption rate**	Approx. 0.05	Approx. 0.28
Laser power	180 W	200 W
Scan speed	600 mm/s	1,000 mm/s
Hatch distance	105 µm	105 µm
Layer thickness	30 µm	30 µm
Scanner time delay (beam on)	0.15 ms	0.2 ms
Scanner time delay (beam off)	0.2 ms	0.25 ms
Beam compensation	0.12 mm	0.065 mm
Scanning strategy	Filling: continuous line w/ meanders at turning points, 90° changing orientation after each layer Contour: none	Filling: continuous line w/ meanders at turning points, 90° changing orientation after each layer Contour: none

*Source: http://www.matweb.com **At ~1 µm wavelength, source: Keyence Corp.

For computed tomography a phoenix v|tome|x s 240 CT system (manufacturer: GE) with scan parameters resulting in approx. 55 µm resolution was used. CT data reconstruction was done with the software phoenix datos|x 2.0 (software publisher: GE). And for QM Meltpool 3D data reconstruction, joint alignment, analysis and visualization of CT and QM Meltpool 3D data the software VGStudio MAX 2.2 (software publisher: Volume Graphics GmbH) was used. In regards to data alignment, same fitting cylinders, planes and point were created in each data set and 3-2-1 alignment method was used. Figure 4 illustrates the complete data processing chain used for the works presented in this paper.

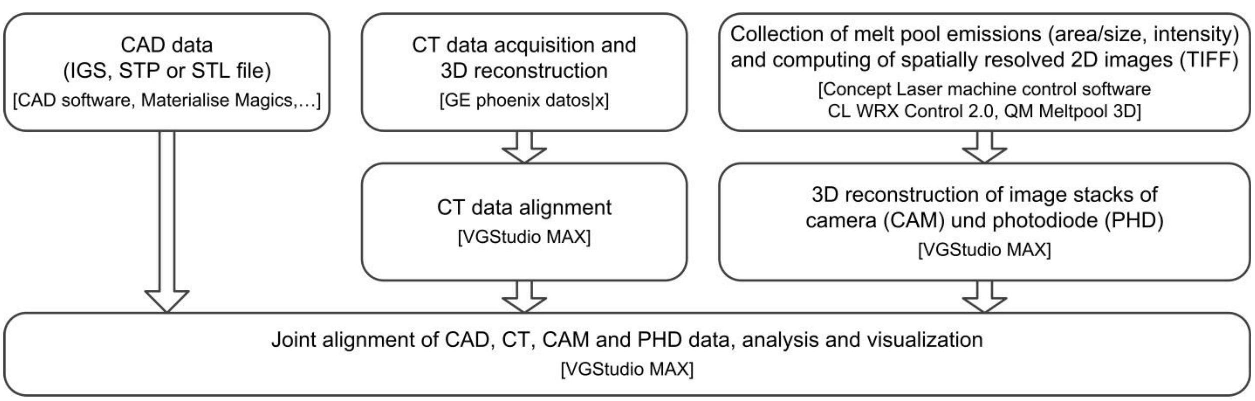

Figure 4. Data processing chain.

<u>Test specimen and experimental procedure</u>

For experimental trials two cylindrical specimens were designed (see Figure 5). Specimen 1 is a multibody design with nine segments to investigate different parameter variations in one sample and therefore reduce effort for later CT scans. In addition, Specimen 2 is designed as single body, 15 mm higher than specimen 1 in order to detect the influence of greater part warming due to shorter interval times between laser operations of consecutive layers.

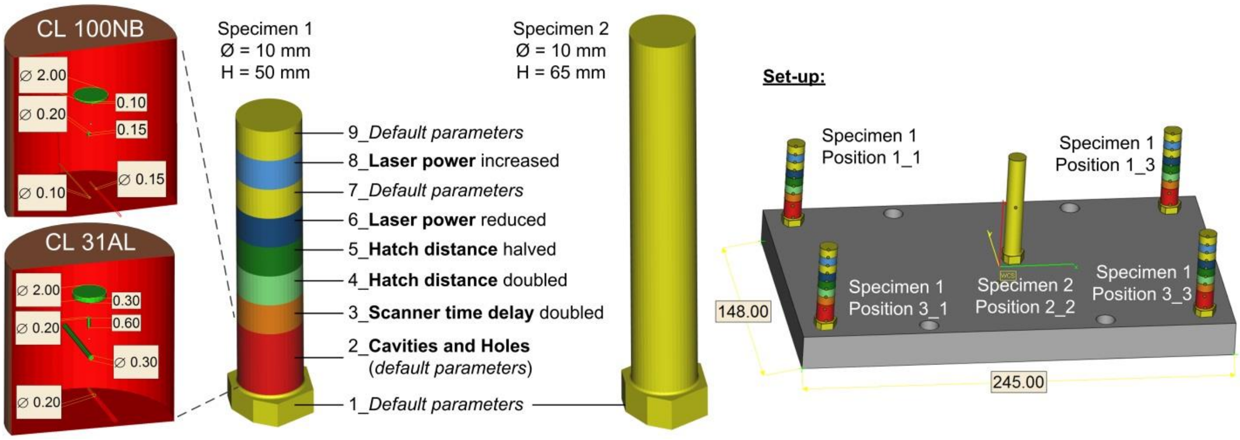

Figure 5. Design of specimen 1 and 2 (center) with detail view of section 2 of specimen 1 (left: magnified sectional view) and set-up of specimens on build platform (right) with sample ID.

Section 1 of specimen 1 is designed as irregular prism for a unique joint alignment of CAD, CT and QM Meltpool 3D data. In section 2 of specimen 1 two cylindrical cavities and two blind holes of different sizes are integrated. Sections 3 - 6 and 8 were manufactured with parameter variations according to Figure 5. Laser power variations used for section 6 and 8 were 150 W and 300 W for CL 31AL material and 90 W and 360 W for CL 100NB. For sections 7 and 9 default parameters were used. In Figure 5, right, the set-up of specimens on the build platform is shown. For each material three build jobs (BJ) were performed. Overall twelve pieces of specimen 1 and three pieces of specimen 2 were manufactured by the respective material. All specimens were separated by wire-cut EDM from the build platform.

Results and discussion

Figure 6 exemplary shows the manufactured test specimen for one build job of each material.

Figure 6. Manufactured test specimen.

In the following, the most important findings are presented. CT data are shown in grey, QM Meltpool 3D camera data (CAM) are shown in green and QM Meltpool 3D photodiode data (PHD) are shown in blue.
All specimens of type 1 manufactured in CL 100NB didn't show any cavities or holes in section 2. The maximum distance in z-direction of all cavities and holes is 0.15 mm, which corresponds to five layers of powder. These were closed by melting of consecutive layers above. This is due to the comparably high absorption of laser energy coupled with low thermal conductivity of this material (cp. Table I). In contrast, the cavities and holes in the CL 31AL samples are pronounced, but as expected, with high porosity in above following layers. This, in turn, demonstrates the small process window for the aluminum alloy. In Figure 7, top, a comparison of CT and CAM data is shown.

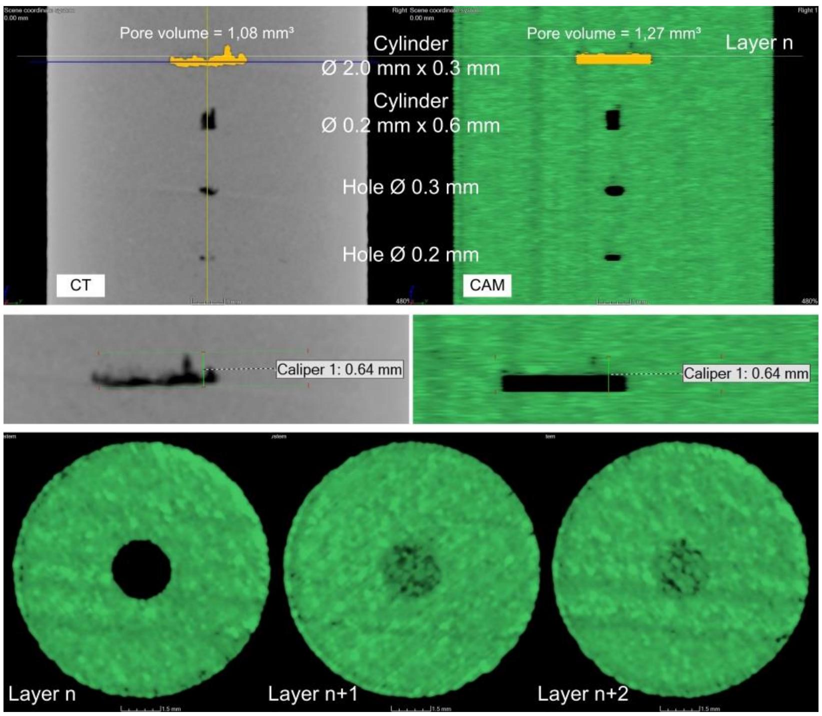

Figure 7. Cross-sectional views through the sample CL 31AL 1_3 of BJ 2 with CT and CAM images from the side view (top), detail view of cylinder Ø 2.0 x 0.3 mm (middle) and view on three consecutive layers (bottom), whereby layer n is the last layer inside the cylinder Ø 2.0 x 0.3 mm and layer n+1 and layer n+2 are the first two layers with melt tracks above the cylinder.

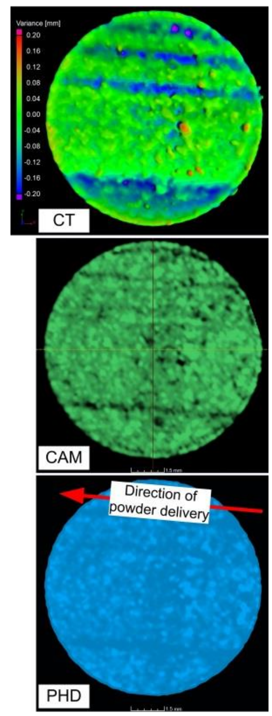

Figure 8. Geometric comparison of CT data to CAD (top) and corresponding top layer of CAM (middle) and PHD data (bottom), sample CL 31 AL 3_1 BJ 3.

The calculated pore volume is indicated above the cylinder and visualized in orange. Due to the fact that the cavities (cylinders) and holes were designed within the CAD data, their original shape is also registered by the camera. The cylinders and holes are slightly bigger in x-y direction because of activated beam compensation for slicing and deactivated contour scanning during manufacturing. This is clearly visible in the cross-sectional view of the two holes, which are rather oval than round shaped. As illustrated in Figure 7, bottom, differences in melt pool emissions between melting in loose powder above the cylinder (layer n+1 and layer n+2) and surrounding solid areas are well detectable and correspond to changes in heat conduction. The

darker the individual pixel/voxel in QM Meltpool 3D camera image is, the smaller is the area of melt pool detected at that position. Thus, above the cylinder significantly smaller melt pool sizes are detected than in the surrounding areas.
In Figure 8 the top surface (CT data) and top layers detected by QM Meltpool 3D are shown. In the CT image (Figure 8, top) increased surface roughness due to mechanical damage of the rubber blade of the powder delivery system are clearly visible leading to significantly grooves (negative variance blue colored). Corresponding smaller melt pool emissions were detected by CAM and PHD, shown in Figure 8, middle and bottom images. Figure 9 shows the cross-sectional view of the CT, PHD and CAM data sets for one specimen of type 1 for each material.

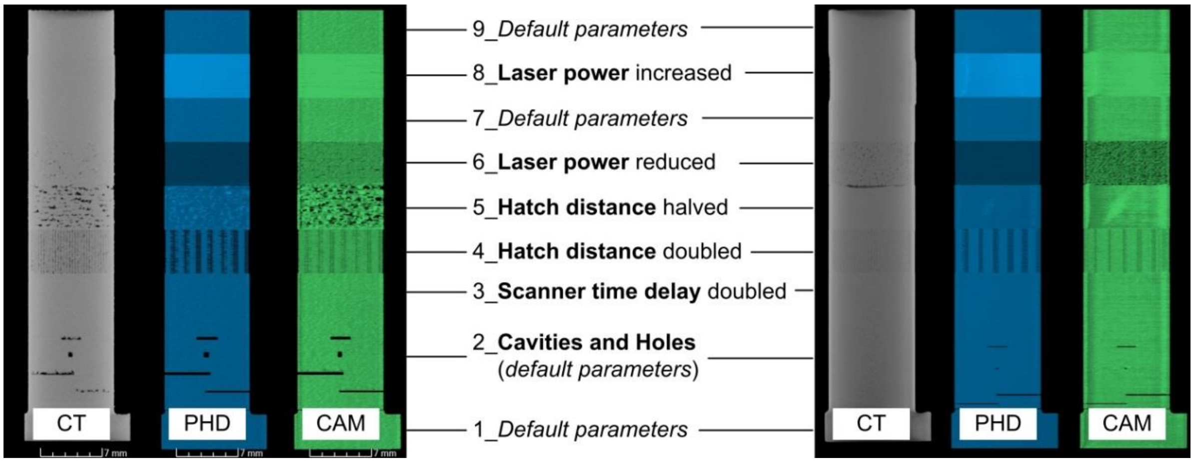

Figure 9. Cross-sectional views through the samples CL 31AL 1_3 of BJ 2 (left)
and CL 100NB 1_3 of BJ 3 (right).

In section 3 no anomalies compared to the sections manufactured with default parameters (1, 2, 7 and 8) were detectable. As expected, section 4 with doubled hatch distance resulted in periodic and evenly distributed porosity. In section 5, fabricated with halved hatch distance, significant differences between CL 31AL and CL 100NB defect shape are noticeable. The aluminum samples contain macro-sized pores distributed within the whole section 5 (Figure 10, left), whereas the nickel samples solely have macro-sized pores on the border to section 6 (Figure 10, right). In both cases QM Meltpool 3D was able detect the particular pore formation, although for small-sized pores cross-layer effects, like remelting underlying layers, make it challenging to exactly localize each single pore. Likewise, greater solid areas in CT compared CAM/PHD data (Figure 10, right) can be explained by cross-layer effects. Reduced and increased laser powers in sections 6 and 8 correspond to lower and higher melt pool emission as shown in CAM and PHD data in Figure 9. Reduces laser power led to increased porosity and with increased laser power no significant changes in density were measureable.

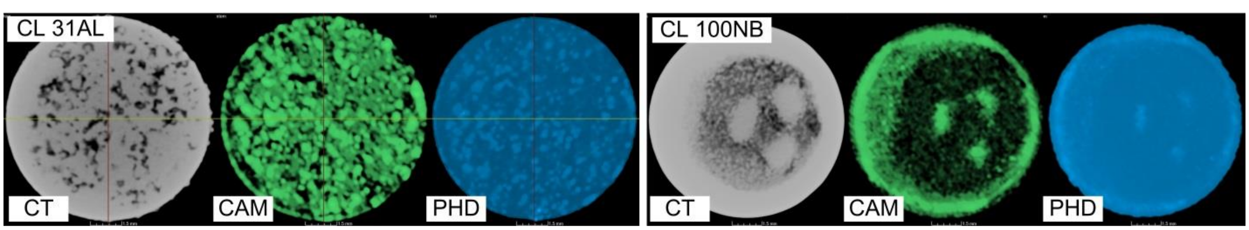

Figure 10. Top view of one layer in the middle section 5 for sample CL 31AL 1_3 of BJ 2 (left)
and one layer just below section 6 for sample CL 100NB 1_3 of BJ 2 (right).

In Figure 11 the results for specimen 2 are shown. Even though, specimen 1 was manufactured as a single body with one set of parameters differences in melt pool emissions are clearly visible. Parallel to each section of specimens 1 significant changes in melt pool intensity were measurable. In this case, differences in interval times between laser operations in the corresponding height of different sections determine dissimilar melt pool emissions. For further investigations, microstructural analyses are in progress.

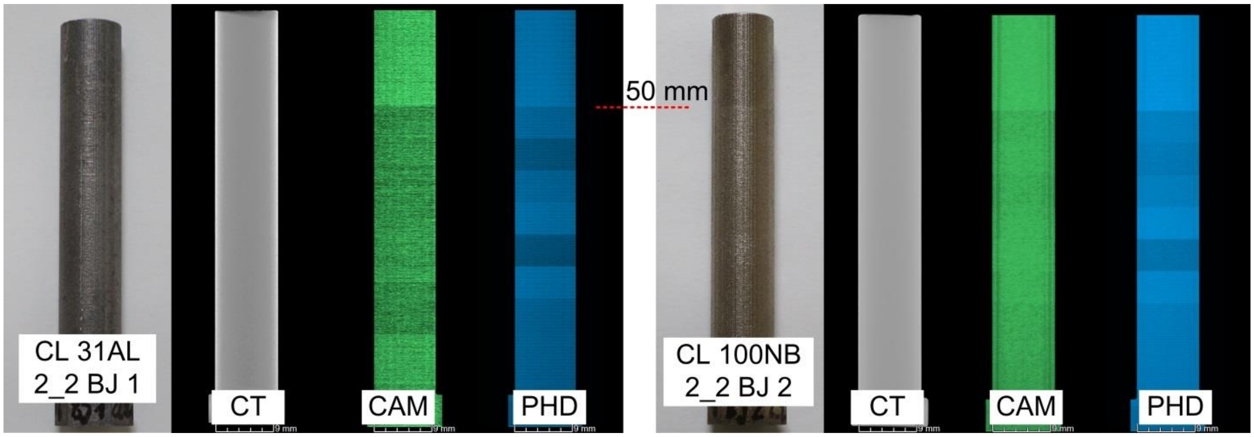

Figure 11. Real samples and cross-sectional views of CT, CAM and PHD data for specimen 2.

Summary and outlook

The works presented in this paper have shown, that QM Meltpool 3D is a powerful tool for real-time process monitoring of the LaserCUSING® process. On the basis of two different materials with great variation in physical properties, CL 31AL aluminum alloy and CL 100NB nickel superalloy, some important analytic capabilities of QM Meltpool 3D were demonstrated. In experiments manufacturing test specimens with variants of parameters, some material-specific as well as cross-material correlations could be shown. The melt pool emissions detected by QM Meltpool 3D correlated well with the resulting part densities measured with computed tomography.

With QM Meltpool 3D it is now possible to log the genesis for each part and layer during the highly complex laser beam melting process. This offers completely new possibilities for quality inspection, material and process development. For safety relevant parts, e. g. found in medical, aerospace or motorsport industry, new opportunities for reduced post process component tests arise from this innovative measuring method and system. Furthermore, QM Meltpool 3D is a first fundamental step for a future self-regulating LBM process control. But before that, more extensive research on correlations between sensor signals and process conditions need to be done.

Present and future works concentrate on cataloguing these correlations in QM Meltpool 3D database. Thus, the basis for an automatic failure detection combined with other measuring principles, e.g. automatic powder supply control (QM Coating), will be extended. This again, will further increase acceptance and use of metal 3D printing and LaserCUSING® in particular for series production, especially for high-tech products. In addition, this will decisively contribute to further process developments of this unique manufacturing technology.

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