Process Monitoring of Additive Manufacturing by Using Optical Tomography

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Abstract

Selective Laser Melting (SLM) is a 3D-printing-process which provides the possibility to construct complex geometries by layered manufacturing of components with metallic powder. At MTU Aero Engines the optical tomography (OT) was developed as an Online Process Monitoring system which documents the complete welding process during the SLM fabrication procedure. Some details of the camera-system are shown. To create probability of detection (POD) curves, different specimens are investigated with digital radiography. To detect the small lack of fusion defects the specimens were plastified in order to increase the volume of the defects. Results of plastified specimens are presented.

1. Introduction

Additive Manufacturing (AM) processes have been investigated since the late 1980s and some of them have become commercially available. With Selective Laser Melting (SLM), components can be produced by localized melting of successive layers of metal powder. Based on CAD-data a fast scanning laser beam is programed to selectively melt metal powder. In comparison to conventional manufacturing techniques, this method allows considerably more freedom in design and also has a tremendous economic potential. It is particularly interesting for the production of geometrically complex components. [1]

Quality assurance (QA) in the field of additive manufacturing is still under development, but especially for aerospace components, ensuring the quality of SLM-parts has a high priority. The size of potential defects is often very small. Therefore, an adequate quality inspection of such parts is rather challenging. However, using conventional non-destructive-techniques (NDT) to guarantee high quality standards is very difficult. Thus, MTU is currently focusing on the development of an Online Process Monitoring system for the SLM fabrication procedure. [2]

In optical tomography (OT) a high-resolution camera system is used to record the welding light intensity of each welded layer. The obtained image stacks are analyzed with image processing algorithms and can be converted into 3D models afterwards by using computer tomography software.

1.1 Selective Laser Melting (SLM)

One of the most spread powder bed fusion additive manufacturing technologies for metallic parts is the selective laser melting process (SLM). This technique uses a laser beam in order to locally melt metallic powder which is applied layerwise. The basic steps of the selective laser melting process are shown in Fig. 1. By these means a near net shape part is produced consisting of layers. Layerthicknesses are commonly between 20 and 50µm. [3]

MTU uses an EOSINT M280 system from Electro Optical Systems GmbH (EOS), which builds the components with a layer thickness of 40µm. After lowering the 250x250mm construction platform, the recoater takes powder from the powder reservoir to coat the base plate. The next step is called exposing, where Ytterbium-doped solid state laser (Yb fiber laser) melts the metal powder at the desired location to form a bond with the underlying and surrounding material. The laser with a wavelength of 1060 to 1100nm and a maximum power of 400 watts has a beam diameter of 100µm. The laser focusing and positioning is accomplished by an F-theta lens and two galvanometer scan mirrors which meander the laser across the metal powder.

During the building process, the build chamber is flooded with inert gas argon to prevent oxidation and nitriding of the material. By means of a ventsystem, the welding smoke produced through the melting of the powder is sucked off and the cleaned argon is returned via a nozzle.

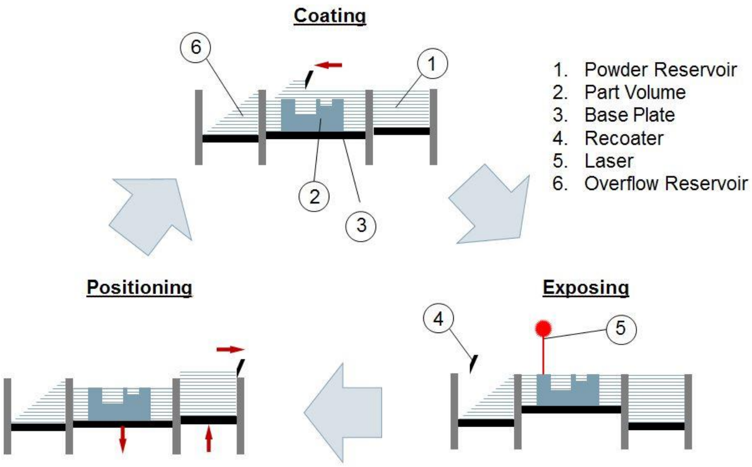

Fig. 1: *Basic principle of the SLM process*

1.2 Optical Tomography (OT)

MTU currently operates six machines of the type EOSint M280, which are equipped with OT systems. The sensor of the OT-camera continuously captures all light emissions of the SLM process and documents this. In the camera system the optics are selected such that the field of view of the camera, corresponds to the size of the platform (Fig. 2).

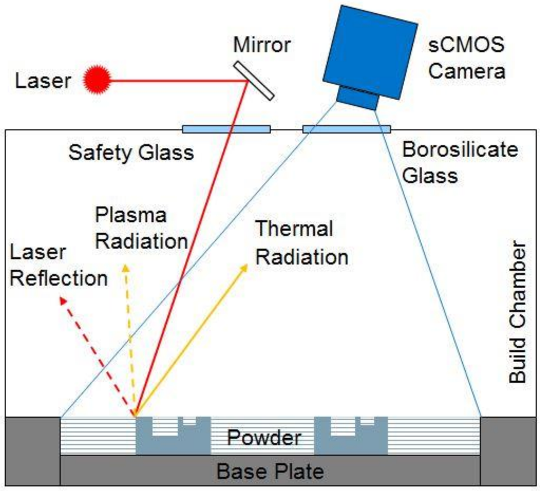

Fig. 2: *Working principle of the Optical Tomography for SLM*

The used OT camera is a pco.edge scientific CMOS (abbr. for: complementary metal-oxide-semiconductor) camera from the PCO AG company (Fig. 3). The camera system has a detector with around 5 Megapixels. Applying this in an area of 250x250mm, it corresponds to a geometric resolution of about 0.1 mm per pixel. The use of a thermal stabilized camera system provides a quantitative evaluation of the radiation intensities. Table 1 lists some specifications of the OT camera.

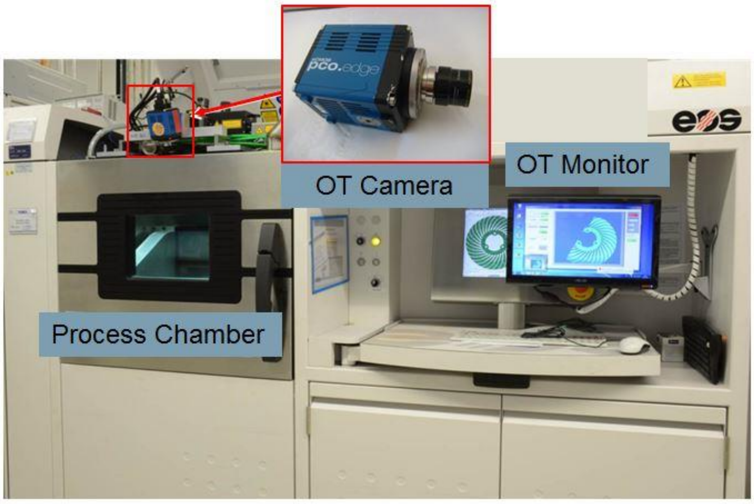

Fig. 3: *OT system with a pco.edge scientific CMOS camera installed on a EOSint M280*

Table 1. *Specifications of the sCMOS camera with filter used for OT*

Used Spectral Range:	900 – 940nm
Sensor Format:	2560 x 2160
Field of View (FOV):	250 x 250mm
Spatial Resolution:	~ 0,1mm
Temperature Range:	800°C – 1200°C
Frame Rate at full Res.:	100Hz
Interface:	Camlink (new: USB)

During the welding process, a glow can be seen at the currently processed position. This emitted radiation mainly consists of three components (Fig. 4). One of them is the reflected laser radiation. Due to the monochromatic nature of laser radiation it is well known that the wavelength of the reflected radiation is 1064nm. In addition, taking into account that plasma emissions can be expected because of the high energy density of the laser at the focal point. This problem happens because high temperatures lead to vaporization and ionization of gases. According to experience these emissions occur in the range between 400-600nm. The spectrum of the emitted thermal radiation ranges from the visible wavelength (380-780nm) to the infrared (~ 14µm).

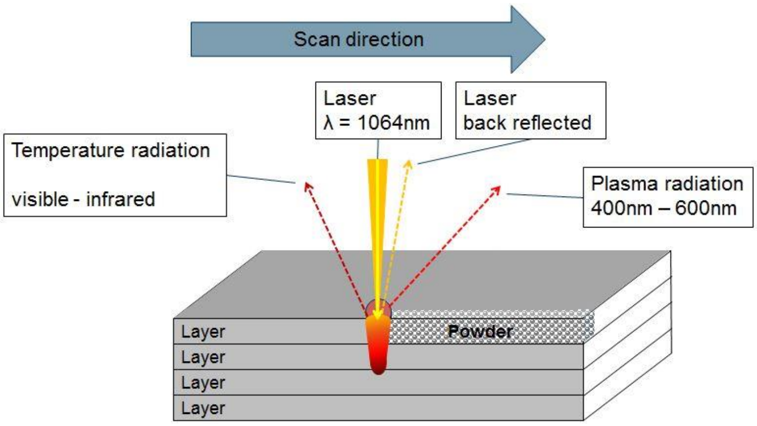

Fig. 4: *Process radiation of SLM*

The information on the process quality are obtained best by capturing the thermal radiation, since this is directly dependent on the properties of the melt pool. Therefore, the thermal radiation must be separated from the other emissions. This is achieved by using a suitable band-pass filter. The high-frequency captured image data are stored in one image at the end of each layer. In Fig. 5 the wavelength dependent sensitivity of the camera is illustrated. In addition, an interval for a filter is shown as an example. The gray-shaded area in the figure describes the permeable wavelength range of the filter which is detected by the OT-camera. [2]

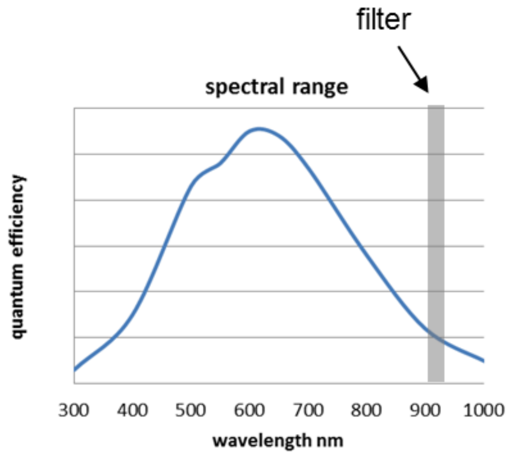

Fig. 5: *Quantum efficiency of the sCMOS camera and spectral filter*

Between image generation and data storage, image operations are performed to reduce noise. Process disturbances, such as welding plume, which leads to defocusing of the laser, are perceived as higher radiation intensity and are stored in the image in the form of higher gray values. By overlapping the welding traces, regular stripes are produced in the pictures, which are called hatching strips. These process-related stripes are present in every layer and must not be interpreted as a deviation. A basic online analysis is executed in the same time. Interference signals are suppressed by means of the adapted spectral filter, so that a correlation between the OT signals and the quality of the welding process becomes possible. [2]

2. Methodology

The welding process temperature range around 1200°C generates radiation energy in the visible or near infrared range of the electromagnetic spectrum which can be used for the measurement with the sCMOS camera. To create POD curves, different specimens are investigated with digital radiography. This allows a correlation between existing material defects and the OT indications. In order to determine the effect of varying wall thicknesses flat tensile specimens are built. The cylindrical tensile specimens should provide sufficient defects for a meaningful POD calculation. Some of the cylindrical specimens have holes to simulate thinner parts. By plastifying the different tensile specimens the defects caused by the lack of fusion are opened to facilitate their detection with x-rays.

2.1 Probability of Detection (POD)

The probability of detecting a material defect is called POD. It is given as a function of defect size and can be determined by experiment. For this purpose, the examined test method is applied to many specimens with material defects of defined sizes. This generates a large set of test results. These are evaluated using statistical methods and the function POD (a) is determined as a function of the defect quantity a. The binary evaluation of the measurement results, in which the measurement result can only accept two values "good" or "bad". This method is called hit/miss method and separates the material defects in detected (hit) and not detected (miss). [4]

2.2 Plastifying

The layered structure during the SLM process results in very thin, flat bonding defects. These were identified as the critical defects due to their areal extent. Fig. 6 shows a metallographic image of such a lack of fusion defect.

Fig. 6: *Metallography of a lack of fusion defect*

However, since the binding defects often only have a height of a few hundredths of a millimeter, they are difficult to detect with computed tomography. Therefore, tensile specimens were manufactured additive and the SLM process was artificially disturbed, by reducing the inert gas flow of the M280 machine. Due to the lower argon flow, the resulting welding fume is only partially exhausted so that defocusing of the laser occurs. In the OT images, this is indicated as a so-called hot spot, because the welding smoke partially reflects the energy of the laser, which is recorded by the SCMOS camera. The samples with the artificially created binding defects were plasticized by means of tensile test systems in order to increase the volume of the defects (crack opening). At a plastic elongation of 5 to 10%, the bonding defects open and can be detected more easily (Fig. 7).

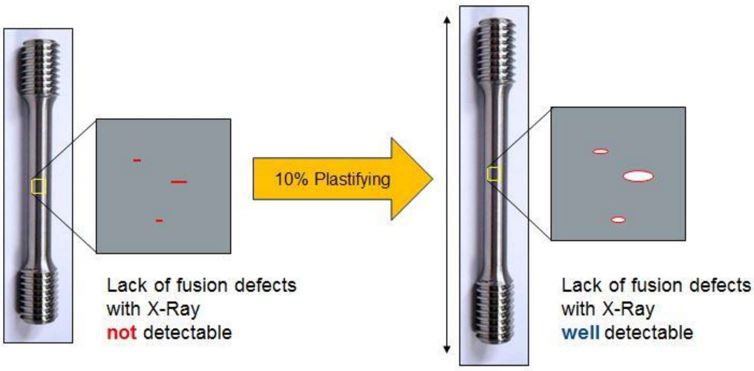

Fig. 7: *"PlastiX" - method to make lack of fusion defects detectable, Patent application DE 10 2016 211 069 A1*

2.3 CT Data and Fusion with OT

After the investigation with radiography the generated CT data are matched with the OT data to find correlations (Fig. 8). For that the CT software Volume Graphics is used. The CT data of a specimen must be compressed to compensate the elongation of the tensile test and they must have a higher resolution than the OT images, because of the size of the real defects. OT indications at the OT volume can be detected with a simple threshold.

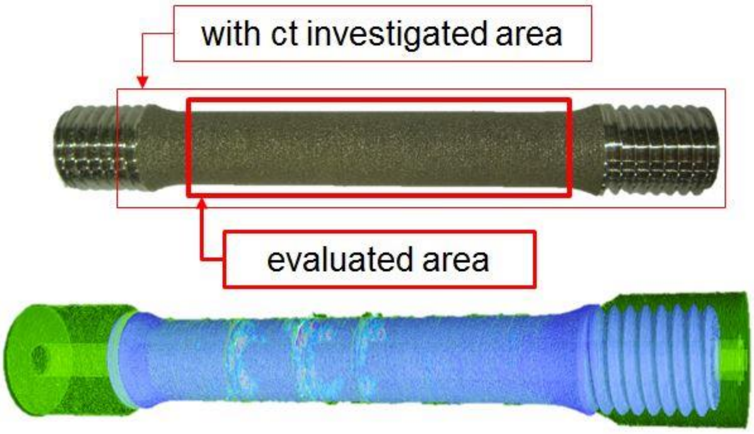

Fig. 8: *above: plasticized hollow tensile specimen; below: fused CT (blue) and OT volume (green), color-coded OT indications*

In Fig. 9, a layer is shown with a “Hotspot” OT indication. The real material defects in the CT volume are colored red in the image next to them. By superimposing the two volumes in Volume Graphics, a perfect assignment of the Hotspot to the lack of fusion defects is possible.

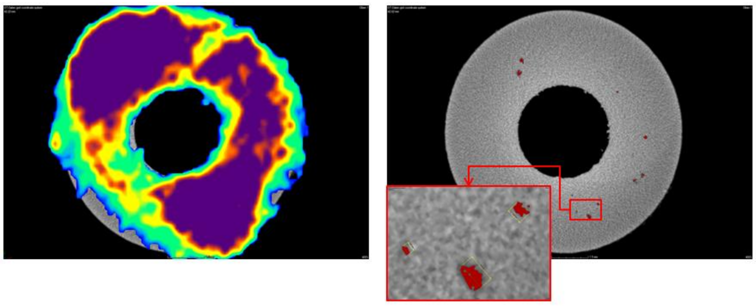

Fig. 9: *left: so-called “Hotspot” OT indication; right: CT data with lack of fusion defects (red).*

3. Results

Initial tests were carried out with massive tensile specimens and a POD was calculated with the determined defect quantities and the associated OT data. In order to simulate even thinner wall thicknesses, the experiment was repeated with hollow tensile specimens, further refining the POD. In these investigations it was also proven that there is an OT indication for every resulting lack of fusion defect, but this does not mean, that every layer with an OT indication also contains real material defects. Binding defects were never found in areas that were not previously marked as critical by the OT evaluation.

4. Conclusion

In order to be able to make a more precise statement about the occurrence of lack of fusion defects in thin-walled structures, specimens with different wall thicknesses have to be built and tested. This can be used to determine which component thickness lack of fusion can be excluded. In addition, the mutual influence of the position of the components on the building platform must be investigated. Closer positioning of thin-walled components could lead to more OT indications.

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