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Observing melt pool temperature fields for process characterization

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Abstract

Thermal processes like welding or additive manufacturing are standard applications in industrial process chains. Using the laser as a heat source can increase e. g. processing speed and energy efficiency. Process results can suffer from sudden changes of process parameters which can induce unwanted pores, spatters, insufficient connection or blow holes. The temperature fields of the material surface can be used to detect process changes and imperfections already during the process. However, optical temperature measurements of thermal processes can be difficult, as the emissivity of the material in the process zone varies depending on temperature changes, melting or even vaporization. In order to guarantee efficient high quality processes for industrial applications a process observation of the temperature is necessary.
Therefore, emissivity compensated temperature measurement systems are evaluated in order to determine their suitability to measure the temperature fields during laser materials processing applications for the detection of process variations. The target application investigated in this paper is laser cladding. Temperature measurements with a standard RGB-camera and a pyrocamera show that the melt pool width can be determined. Process variations of powder application, velocity and focal position can be distinguished from the temperature field.

Keywords: Temperature field analysis; Laser materials processing; Additive manufacturing; Laser cladding

1. Introduction

Laser deposition welding is a method to produce layers on specimens by applying powder or wire that is molten by a laser heat source. That way, complex structures can be built for surface cladding, e. g. in Kathuria 2000, repairing, e. g. in Koehler et al. 2010, rapid prototyping or production of parts. Process changes due to variations of the welding parameters or process defects can significantly influence the resulting seam, as e. g. determined by Chryssolouris et al. 2002, and can therefore produce defective parts.

In order to identify those errors during the process, observation methods can be used. When process parameters vary, the weld seam geometry on the material surface or the temperature field can change. Therefore, these characteristics can be used for process observation. Usually, the seam is detected using high speed cameras, as shown e. g. by Hofman 2009. However, temperature measurements are more complicated to conduct. Thermocouples usually cannot resist the environment in the process for directly measuring the melt pool temperatures. Thermocouples are damaged after the process when they were used for melt pool measurement and cannot be re-used. Additionally, a temperature distribution measurement in the comparably small melt pools with an acceptable resolution is not possible.

Optical measurements can be used to observe the material surface. Due to the different surfaces appearing during the process depending e. g. on the temperature of the material and its partial melting, the emissivity of the surface constantly varies and makes a temperature measurement challenging. The reason is the change of the emissivity of objects depending on the temperature and phase. Especially at high temperatures with high temperature gradients, as they

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appear during thermal laser processes, the emissivity plays an important role for temperature measurement. Therefore, emissivity compensated measurement methods are preferable. Quotient pyrometers offer that possibility by using two different wavelengths for the temperature measurement, but these systems usually use one measuring spot or a line to identify the integrated temperature but cannot determine a temperature field as summarized by Doubenskaia et al. 2006. An emissivity compensated 2D-detector pyrocamera introduced by Hutter et al. 2008 offers the possibility to measure emissivity compensated temperature fields. Koehler et al. 2013 could show that these emissivity compensated systems can be used for observing laser cladding processes. This work was continued in Koehler et al. 2016.

Usually, an external observation of the process zone is used, as e. g. shown by Bi et al. 2006. The development of an innovative laser system by OSCAR PLT as shown by Freiße et al. 2016 for additive manufacturing offers new possibilities for process guidance but presents new challenges for welding observation. This direct diode laser system offers the possibility for direction independent processing by a circular arrangement of the diode stacks with a central application of wire or powder. For a robust setup a temperature measurement system should be implemented into the welding head.

Therefore, the aim of this work is to evaluate methods for process observation through the welding head. It is the first time to analyze the possibility of observing temperature fields through an endoscope based optical system. The goal is to measure temperature fields during transient thermal laser processes in order to detect and analyze process changes.

2. Equipment and processes

2.1. Direct diode laser

A newly developed direct diode laser from OSCAR PLT GmbH was used for the experiments. The laser diodes are integrated into the laser welding head, so no optical fiber for beam delivery is needed (Fig. 1a). Due to its low weight the laser head can be mounted e. g. directly to a robot. Several laser diodes are placed in a circle in the laser head and are combined by the focusing lens in the focal position (Fig. 1b). Two wavelengths of the diode laser systems are used (916 nm and 980 nm). The additional material is applied through the center of the welding head. In this work, a powder application was used. The powder nozzle reaches through the welding head and the hole in the focusing lens to the process zone. This setup offers the possibility for highly efficient, direction independent processing.

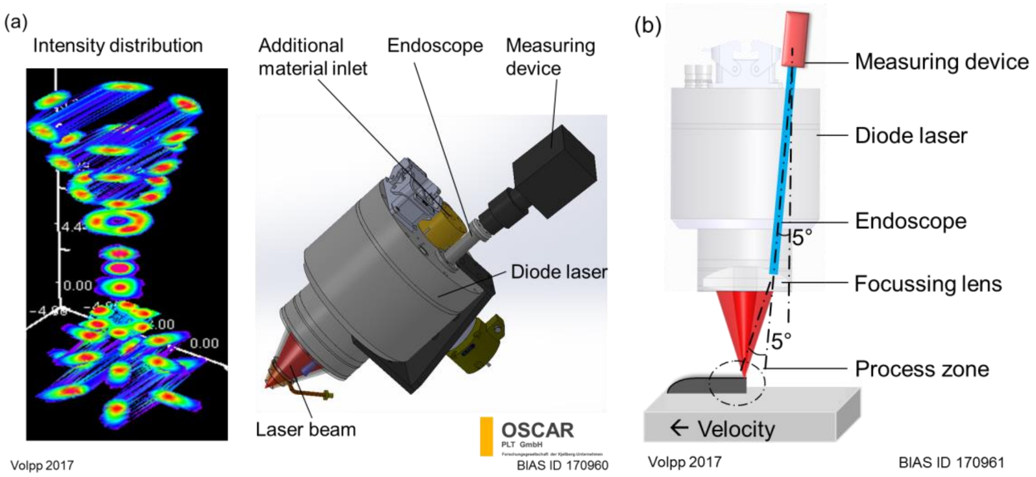


Fig. 1. (a) Diode laser with focal beam intensity distribution; (b) Sketch of the process configuration

In order to integrate the process observation system into the laser head a specially developed endoscope (Hinze OptoEngineering) was used on which the measuring device can be mounted. The front end of the endoscope was positioned above the focusing lens. The endoscope was mounted with a 5° angle to the vertical axis and shows a 5° angled observation view. In front of the measuring device a neutral density filter (absorptive OD2-filter) for reducing the overall intensity and a low-pass filter (900 nm) for cutting off the laser radiation were integrated in the optical path. The abbreviation OD stands for optical density of a neutral density filter and describes the measure of the transmission. In this case the transmission is 1 %.

2.2. Processes

Two processes were observed in this work at varied welding velocity and focal position in order to identify the potential of detecting process properties using temperature field analysis. The laser was used for processing the surface of the base material (mild steel S235JR, Table 1) with and without powder application at otherwise same parameters (Fig. 2). Argon was used as shielding gas at 10 l/min flow rate at a laser power of 500 W.

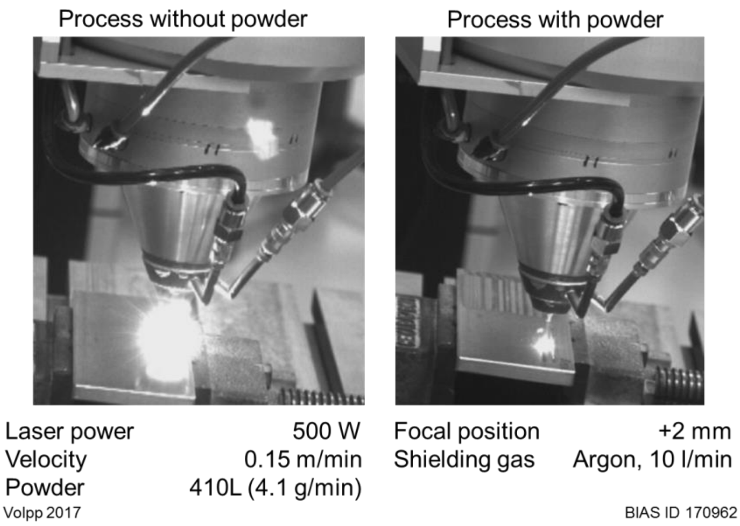


Fig. 2. Processes with and without powder application

The powder application was conducted through a 0.8 mm diameter nozzle positioned 18.6 mm above the work piece at a divergent flow with a full angle of 24°. The powder 410L (53 µm to 150 µm, Table 1) was applied at 4.1 g/min using a powder delivery system with Argon (3 bar) as carrier gas. The specimen is of the size 100 x 50 x 8 mm^3 and 40 mm long seams were produced with and without powder application.

Table 1. Chemical composition of the used materials (data according to manufacturers` specifications)

wt-%	Fe	C	Mn	P	S	N	Cu	Cr
S235	basis	0.17	1.4	max. 0.035	max. 0.035	0.012	0.55	-
410L	87.5	-	-	-	-	-	-	12.5

2.3. Temperature measurement

A pyrocamera (IMS Chips HDRC© Q-PyroCam) and an RGB-camera (TheImagingSource DFK 23GV024) were used for temperature measurements in this work. Both systems use wavelengths in the visible spectrum for the measurements. This is mandatory as wavelengths in the NIR (near infrared) cannot be transferred through the optical system.

The pyrocamera records frames with a chip of the size 640x480 pixels at up to 40 Hz frame rate. The emissivity compensation of the material surface emissions is achieved by using two measuring wavelengths (661 nm and 677 nm). Pyrocamera temperature frames give the temperature distribution in the range between 600 °C and 1900 °C.

The RGB-camera provides frames at 752x480 pixels at 40 Hz frame rate. In order to determine the temperature from the RGB-frame a calculation is needed. Based on the sensitivity spectrum of the camera pixels of the individual colors of the sensor (provided by TheImagingSource) and the assumption of a black body emission of the specimen, the ratio of the red intensity to the blue intensity values is used to calculate the temperature value as demonstrated e. g. by Tanaka et al. 2014. The RGB-camera gives values in the range of 0 °C to 5000 °C. As single pixels can see no or very high intensities in one frame due to reflections or other disturbing effects, the calculation of the ratio of blue and red pixel values can lead to a wrong calculation of the temperature in single pixels and therefore to artefacts (white and black pixels) in the RGB-frames.

3. Methods

3.1. Melt pool observation

The temperature fields from the cameras were used for the evaluation of the process zone during laser processing. Fig. 3 shows examples of frames taken with the pyrocamera and the RGB-camera and the observed areas with and without powder application.

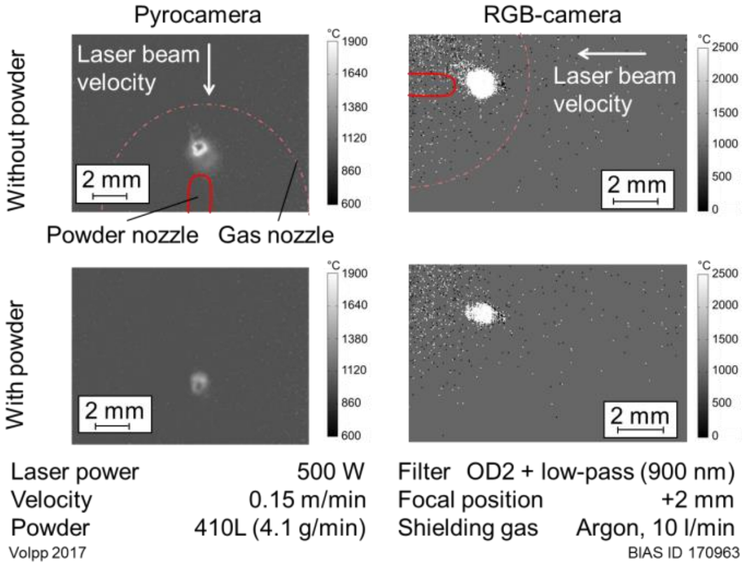


Fig. 3. Camera observation of the melt pool using the pyrocamera and the RGB-camera at different processes

For the evaluation, the molten zone was determined by a Matlab (Version R2009a) routine detecting the pixels with higher temperatures than the melting temperature of the base material of 1500 °C. This area is taken to evaluate the melt pool widths (Fig. 4). When five pixels in one line show a higher temperature than the melting temperature, the melt pool beginning and end is defined. The maximum width of all pixel lines is defined as the melt pool width. Good process results regarding smooth weld seam appearance were observed at a focal position of +2 mm above the work piece. According to Fig. 1a the beam is slightly wider with a reduced intensity in the center.

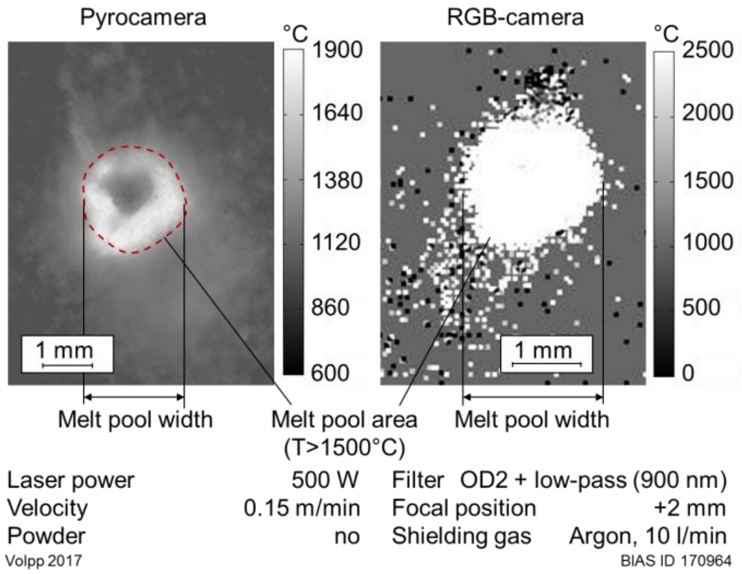


Fig. 4. Melt pool measurement in pyrocamera- and RGB-frames

3.2. Seam measurement

For the seam evaluation cross section are prepared. In the cross sectional pictures the seam width is determined as shown in Fig. 5.

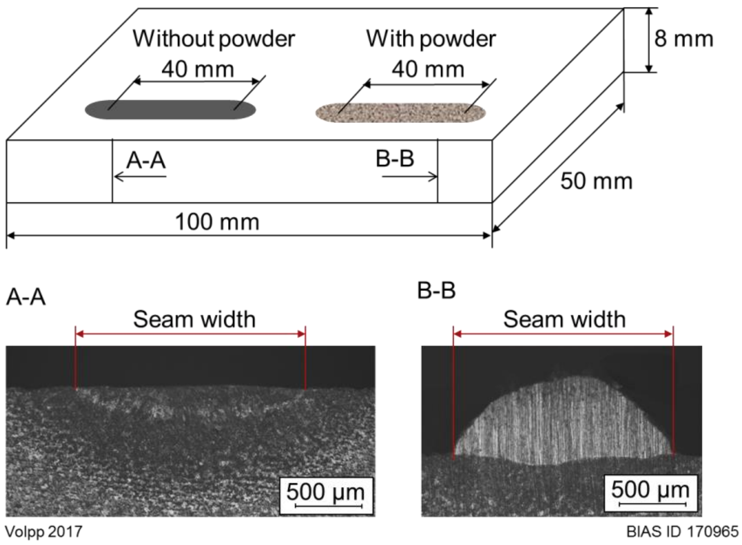


Fig. 5. Seam measurements without and with powder application

4. Results

4.1. Temporal melt pool behavior

Melt pool width was detected in each frame. The temporal behavior of the melt pool width is shown in Fig. 6 (and in the Appendix, Fig. A1) without powder application when using the pyrocamera and the RGB-camera. The camera evaluation shows mainly constant melt pool widths. At low welding speeds instabilities occurred during the process which produced a bulging and melt ejections which lead to the temporarily decreased values. The mean value is taken as the average melt pool width.

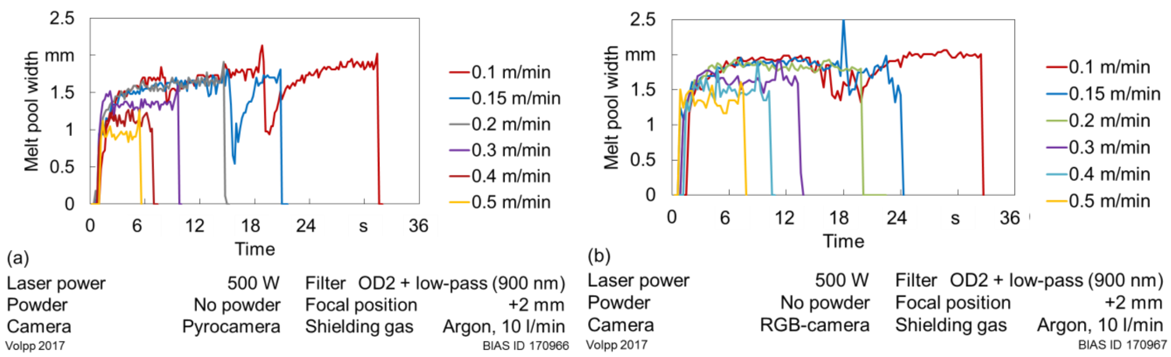


Fig. 6. Temporal melt pool width recorded with (a) the pyrocamera and (b) the RGB-camera

When applying powder during the process the variations of the detected melt pool widths are generally higher (Fig. 7 and Appendix, Fig. A2). At low welding velocities the pyrocamera is able to detect the melt pool width at low variations. At higher welding velocities the melt pool cannot be recognized by the pyrocamera anymore due to the lower energy per unit length at high powder absorption resulting in low thermal radiation to the measuring device (Fig. 7a). The RGB-camera shows big variations of the melt pool widths at all observed parameters (Fig. 7b).

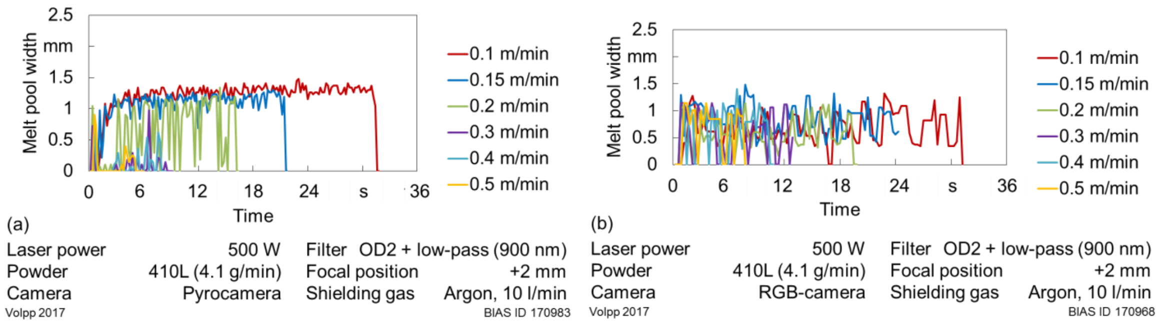


Fig. 7. Temporal melt pool width with powder application recorded with (a) the pyrocamera and (b) the RGB-camera

The evaluated average melt pool widths detected with the cameras are summarized in Fig. 8. The melt pool width detected at no powder application are, in general, higher than with powder application. When using no powder, an increasing welding velocity leads to a decrease of the melt pool width while at different focal positions the melt pool width does not show significant variations. When using powder at high velocities, the pyrocamera cannot properly detect the melt pool width anymore while the detected widths from the RGB-camera show no significant variations. However, at increased focal positions the RGB-camera cannot detect the melt pool properly anymore while the value of the pyrocamera does not significantly vary.

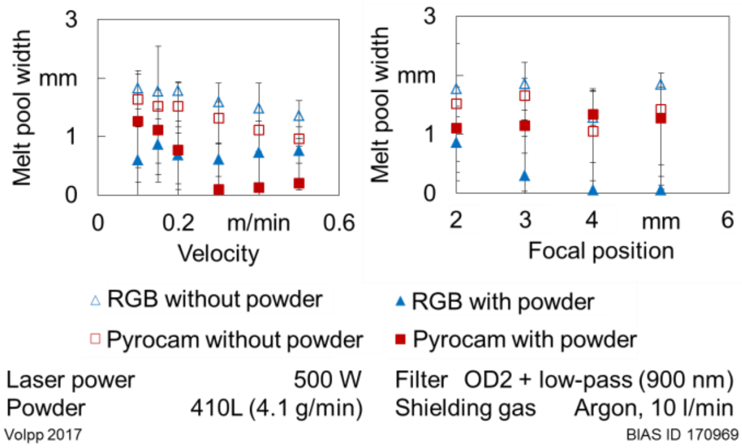


Fig. 8. Melt pool width depending on process parameters

4.2. Seam width measurement

The seam width measurement from the cross sectional images is summarized in Fig. 9. When applying powder, the seam width is slightly smaller than without powder. Due to the energy needed to melt the powder the base material is only partially melted while the additional material builds the seam (Fig. 5, B-B).

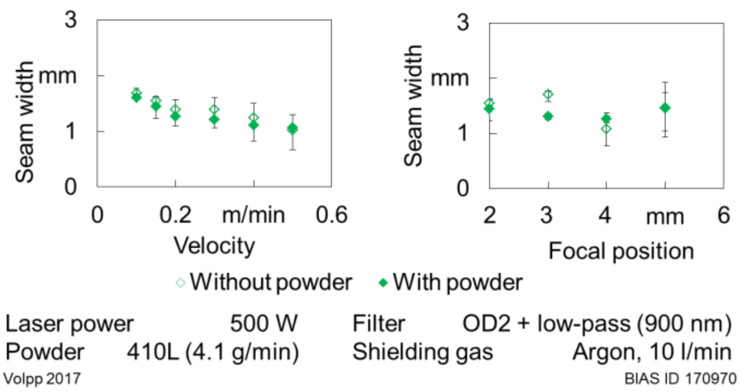
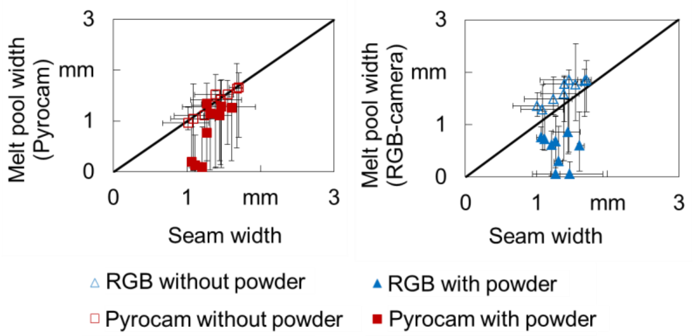


Fig. 9. Seam width measurements at different parameters

5. Comparison of measuring setups

The two temperature field measuring systems show different possibilities for process observation through the endoscope. The deviations of the measured melt pool widths to the seam widths are compared in Fig. 10. It can be seen that the seam width can be reliably detected with the measurements of the cameras when welding without powder. Measurements of the melt pool widths are, in general, possible with both configurations.



Average deviation from measured seam width

	Pyrocamera	RGB-camera
Without powder	+11 %	+17 %
With powder	-31 %	-54 %

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Fig. 10. Comparison of detected melt pool widths and resulting seam widths for (a) RGB- and (b) pyrocamera

However, the RGB-camera underestimates the melt pool dimensions when applying powder. The low values of the melt pool widths with powder application seem to be related to the scattering of the light by the particles. That way, it seems that not enough intensity from the process can be transmitted through the particles to the measuring device and too low temperature values are calculated.

However, the seam widths with powder application can be detected in the 2D-frame of the pyrocamera. Only high processing velocities lead to a false detection. The error bars of the measured melt pool width in Fig. 10 show that occasionally low melt pool widths are detected which has to be considered when applying this method for quality insurance applications.

6. Conclusion and Outlook

- It is possible to measure temperature fields through an endoscope optical system implemented in a direct diode laser during laser applications.
- A weld seam detection is possible with both an RGB-camera and a pyrocamera, while the pyrocamera shows more reliable values of the seam width measurements.
- Compared to the RGB-camera the pyrocamera measurement is able to detect the melt pool dimensions properly at low welding speeds.
- Variations of process parameters are indicated in the melt pool dimensions of the temperature frames and can therefore be used for future quality assurance systems.

Further work of the partners will therefore be done to increase the illumination level of the camera chips by e. g. using an improved endoscope. The aim is the implementation of the process observation into a quality control system.

Acknowledgments

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Appendix

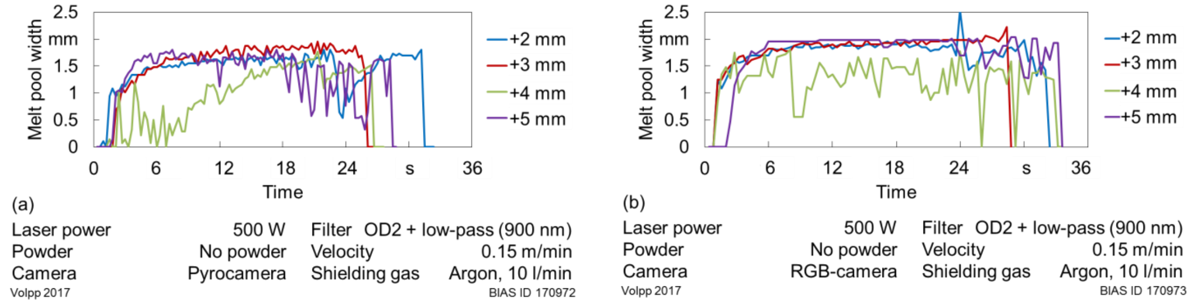

Fig. A1. Temporal melt pool width at varied focal position without powder application

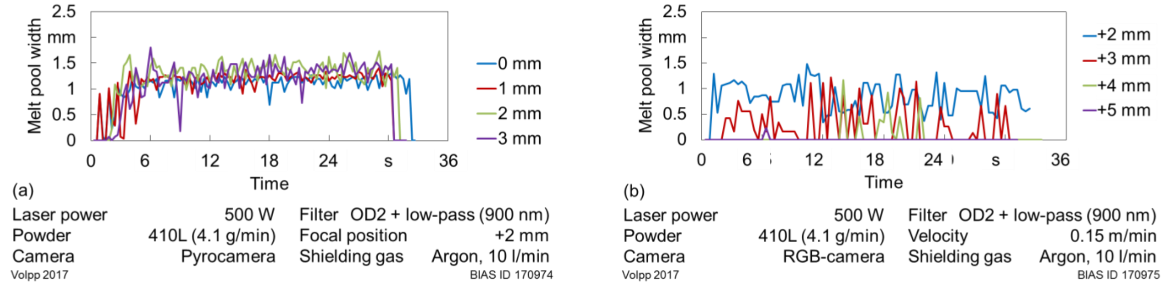

Fig. A2. Temporal melt pool width at varied focal position with powder application