Lasers in Manufacturing Conference 2023

In-process monitoring and measurement of track geometry for laser metal deposition with laser triangulation

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Abstract

Laser metal deposition (LMD) is an additive manufacturing process which is used for reconditioning components or generating components. During the process, the welding tracks are affected by complex temperature-time gradients that result in geometric deviations. The width deviation causes changing overlaps, which increases the effort for post-processing and limits the build-up rate.
The present work describes a novel in-process monitoring approach for LMD with a new developed and robust laser triangulation sensor from Falldorf Sensor GmbH. It is characterized by having a low height deviation compared to a confocal microscope. The results show that the layer height and width with its peaks and valleys can be monitored even in harsh environments and with a small distance to the process zone (10 mm). These aspects provide a solid basis for a further control of the layer topology.

Keywords: laser metal deposition; in-process monitoring; triangulation sensor

1. Introduction

Laser metal deposition (LMD) is an additive manufacturing process to generate large components or recondition machine parts. Here, metal powder is deposited with carrier gas through a nozzle and is melted layer by layer with a laser. Due to many different dependent parameters, such as laser power, feed rate, powder mass flow, laser spot size etc. LMD is a highly complex process. The growing part volume, which leads to a continuous change in heat dissipation, together with the duration of energy input constantly influences

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the thermal conditions of the process. This changes the size of the melt pool and thus the shape of the solid welding track (Donadello et al. 2022).

When the track height changes during the process the working distance of the nozzle changes when several layers are built up, which means that the powder stream is not focused and less powder is deposited in the welding track. A varying track width changes the overlap when creating surface coatings using side-by-side tracks and constant offset between the tracks. This may result in deeper valleys between the tracks, which increases the distance between valleys and peaks and thus reduces the effective layer height. The higher the distance difference the more post-processing is required and more material has to be deposited to achieve the desired layer thickness. This increases the amount of work and the material consumption, which consequently leads to higher production costs. Both geometric deviations can limit the build-up process, so constant thermal conditions must obtain to generate a uniform surface structure (Tyralla et al. 2020).

A common method to monitor the track geometry is to detect the size of the melt pool using a camera or the temperature with a pyrometer to get information about the thermal conductions of the process and conclude about the track geometry. Another method is to measure the height of the melt pool with an optical coherence tomography (OCT) and use a numerical simulation to calculate the geometry of the solid track or to measure the actual track height after solidification with a laser triangulation sensor. Both methods temperature and height measurement can be used for a closed-loop control system of the track geometry (Baraldo et al. 2020); (Kogel-Hollacher et al. 2020).

In the present work a line laser is projected onto a substrate surface and the reflected beam is detected with a photosensitive element. With using a defined angle and the triangulation relationship between laser source, measurement object and receiving part, conclusions about the distance and thus the height of the object can be reached (Chen et al. 2022). In addition to the lateral arrangement, the triangulation laser beam can also be integrated coaxially into the optics and guided parallel to the processing laser. The focusing lens deflects the beam and creates a small triangulation angle for height measurement to pass the nozzle. Here, a single laser point is used that detects only one height value, while the line laser captures an entire profile line. However, the significantly lower triangulation angle results in lower height resolution. (Donadello et al. 2018); (Swojak et al. 2021)

This paper presents a prototype laser triangulation sensor from Falldorf Sensor GmbH, as an in-process monitoring device for LMD processes. In this case, the sensor is tested the first time and used to detect multiple overlapping tracks to measure the peaks and valleys and thus the effective layer height using a LabView program. Furthermore, the new sensor is validated with an offline measurement by using a confocal microscope.

2. Experimental & methodology

The experimental setup consists of a 3 kW diode Laserline laser LDM 3000-30, a Laserline Zoom OTZ-5 VC optics with a GTV PN6625 nozzle. The processing laser has a wavelength between 900 nm to 1080 nm. The optics can be used to increase the laser spot size from 1.0 mm up to 3.6 mm without focus shift. The structural steel S235 substrate was mounted on a 3-axis CNC machining station in powder focus which is set at a distance of 25 mm to the nozzle. On the substrate, 5 side-by-side tracks with a length of 40 mm were welded unidirectionally with 316L powder and laser power between 800 W and 2600 W. The powder from DEW Deutsche Edelstahlwerke has a grain size between 45 µm and 106 µm.

The height data were measured in-process by a newly developed laser triangulation sensor from Falldorf Sensor GmbH. With its wavelength of 405 nm and optical filters the prototype has the ability to work even on hot surfaces and suppress disturbances from the process light emissions. It has a measurement rate of 100 Hz. While the lateral field of view is about 20 mm, the vertical rage is approximately 15 mm. In both directions the resolution is around 20 µm. The sensor was mounted in tailing position and angled at 13° to reduce the horizontal distance to the processing laser spot to 10 mm. A schematic view of the LMD process and the actual experimental setup is shown in Figure 1.

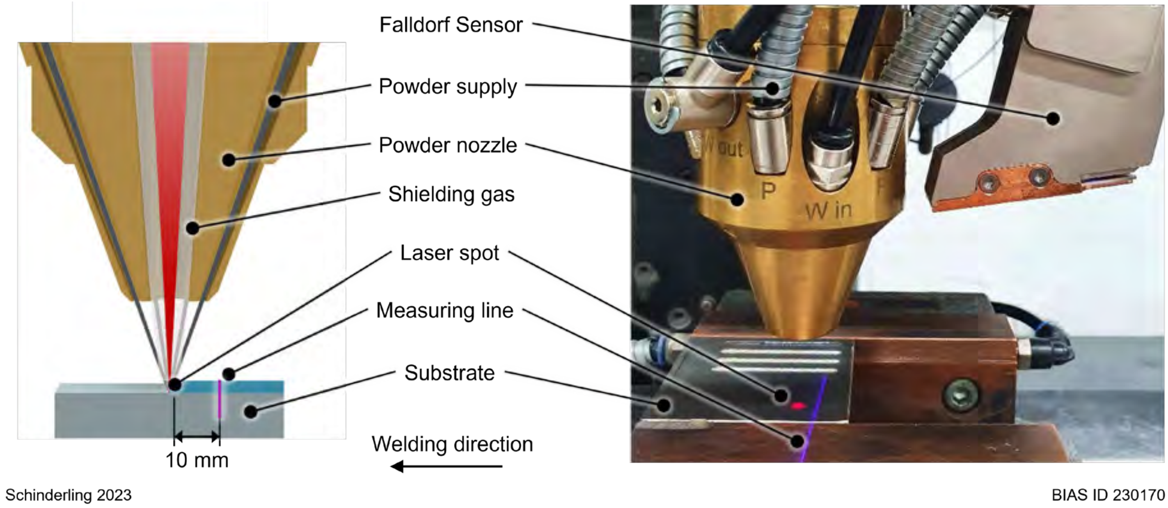


Fig. 1. Schematic view of the LMD process (left) and real experimental setup with trailed Falldorf sensor (right).

The associated Software JTrack from Falldorf Sensor GmbH converts the sensor data into height data of a single profile line and transmitted the averaged values of 5 profiles via ethernet protocol to a National Instruments (NI) controller cRIO 9030. A plugged-in NI 9205 module is connected to the CNC-machine and receives a 5 V signal each time the processing laser is turned on. Besides a 24 V power supply (NI PS-15) and a laptop with a LabView program is also connected via ethernet to the controller. A LabView program on the controller filters the raw data, which is used to determine the highest peak, lowest valley, width, and average height of the entire layer. A graphical user interface (GUI) displays the filtered and raw data on the connected laptop. To remove measurement artifacts, the height data (Z-data) are cut, leveled, smoothed and the projection distortion which is caused by the 13° angle of the sensor as well as the slope of the substrate is subtracted. Temporal fluctuations of the measured values are filtered by calculating a moving average of the last 5 profiles. To evaluate the influence of the laser power on the overlap of the side-by-side tracks the laser power was varied between 800 W and 2600 W. The following parameters are kept constant, see in Table 1:

Table 1. Constant parameters for overlapping tracks.

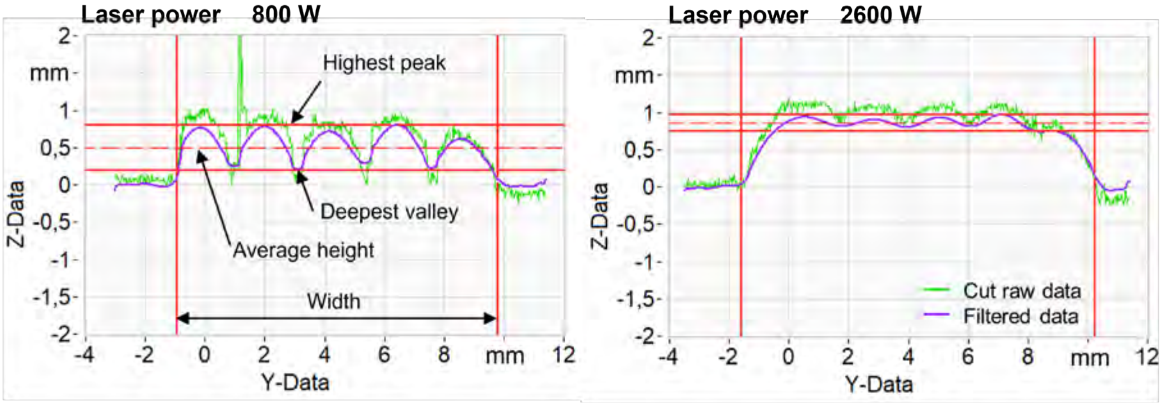
Feed rate	800 mm/min
Laser spot diameter	3.0 mm
Powder mass flow	16.5 g/min
Carrier gas flow	10 l/min
Shielding gas flow	15 l/min
Track numbers	5
Offset between tracks	2.16 mm
Track length	40 mm

To verify the results of the new Falldorf sensor single tracks were monitored in-process and measured afterwards with a Keyence confocal microscope VK-X 3000, with a vertical resolution of 0.5 µm.

3. Results

Figure 2 displays two recordings of the triangulation data by welding 5 tracks with an offset of 2.16 mm produced at low (800 W, left) and high (2600 W, right) laser power. It shows the leveled and cut raw data (green profile line) and the filtered data (purple profile line) which are used to determine the measured values. Here, the currently welded track is located at Y = 0 mm. It can be seen that the filtering smooths the raw data and removes outliers, as seen in the left graph at position Y = 1 mm. The upper horizontal red lines represent the highest peak and the lower red lines the deepest valley of the layer (i.e the effective layer height representing the maximal height that may be used after machining). The middle-dashed red lines are the average layer height and the vertical red lines shows the width of the entire layers.

At a very low laser power of 800 W (Fig. 2 left) the tracks are almost separated from one another, and the large vertical distance between the peaks and valleys striking. It can be seen that such deep valleys which occur at low laser power can be detected correctly by the system. At very high laser power of 2600 W (Fig. 2 right) the comparatively smooth surface with flat valleys can also be detected well and undisturbed by excessive heat from a hotter and larger melt pool at a very short distance from the measuring zone.



Laser	LDM 3000-30	Powder material	316L
Optics	ZOOM OTZ-5 VC	Powder mass flow	16.5 g/min
Powder nozzle	GTV PN6625	Shielding gas	15 l/min
Triangulation sensor	Falldorf Prototype	Laser power	800, 2600 W
Distance laser spot/sensor	10 mm	Feed rate	800 mm/min
Laser spot diameter	3.0 mm	Offset between tracks	2.16 mm

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Fig. 2. LabView recording of leveled raw (green) and filtered data (purple) with measurement lines (red).

Figure 3 shows on the one hand the in-process height measurements with the triangulation sensor (green line) and on the other hand the offline measurement with the confocal microscope (gray line) for a single track. For the measurement with the confocal microscope 242 cross sections with a distance of 165 µm where evaluated which corresponds to the same measurement interval as the triangulation data. Both methods have almost the same course. Considering several single tracks, the deviation of the measurement results was (24±11) µm.

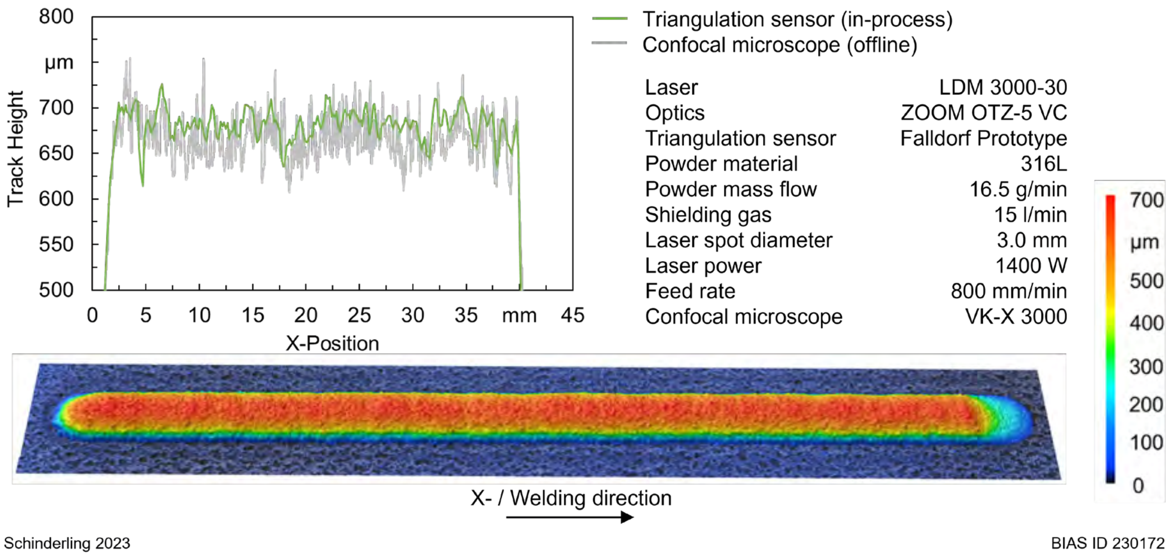

Fig. 3. Comparison of height measurement with triangulation sensor and confocal microscope.

In Figure 4, 5 overlapping tracks are welded with laser power between 800 W and 2600 W. The left diagram shows the in-process measurement results of the highest peak of all 5 tracks and the right diagram the distances between the highest peaks and lowest valleys. Here, track 1-2 is the measurement during the welding of the first and second track and so on. As already seen in Figure 2, the distance here also decreases with increasing laser power, but above 1400 W it remains almost the same. There are also stronger fluctuations of the distance at lower laser powers such as 800 W visible. In addition, in the left diagram it is noticeable that the peaks in the first track are considerably smaller than in the following. Between track 2 to 5, no significantly differences can be seen in the measured values. This can also be observed in Figure 2, where the first track (on the right in each case) is significantly smaller.

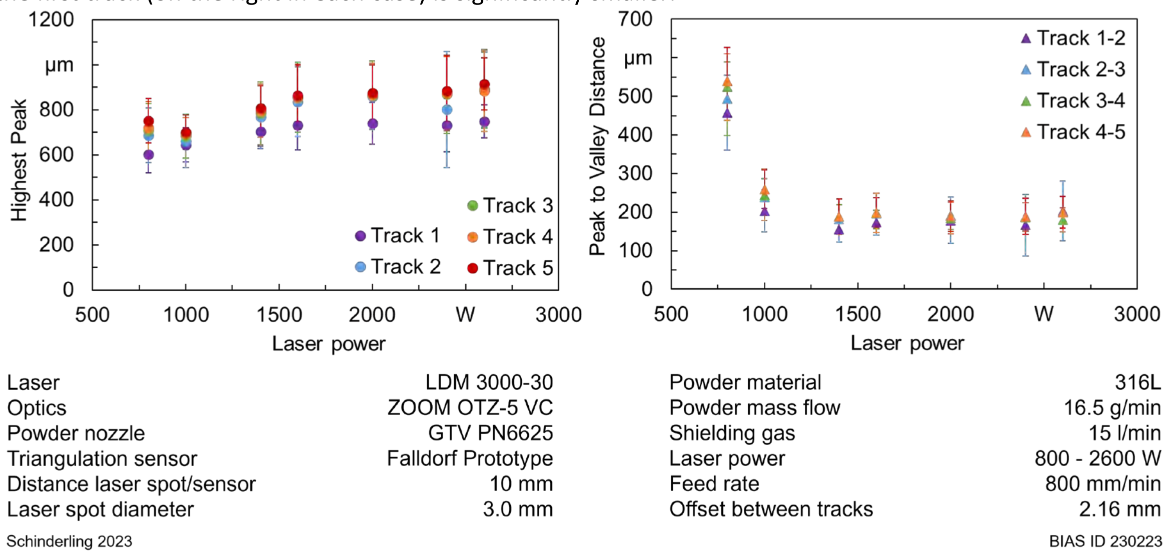

Fig. 4 Influence of laser power on layer peaks and valleys.

4. Discussion

The results shows that the new Falldorf sensor is a viable in-process monitoring device for LMD processes to detect peaks and valleys of a layer in harsh environment, which can be seen in Figure 2. Here, deep valleys at too low a laser power (800 W), as well as layer surfaces at high laser power (2600 W) can be reliably detected. It can be seen that both, the powder stream and hot processes barely disturb the in-process measurement. The reason for this is the 405 nm wavelength and the optical filter of the sensor which makes it possible to measure extremely close (10 mm) to the process zone. In addition, the LabView program is used to smoothen the raw data and remove outliers.

The verification of the prototype with the confocal microscope shows a small deviation of (24±11) µm between the in-process and offline measuring methods. This is also shown in the diagram of Figure 3 where the height profile is nearly the same. The main reason for the deviation is the 40 times higher resolution of the confocal microscope against the triangulation sensor, however, the sensor can detect the surface of a single track reasonably well.

Figure 4 shows, that the distance between peaks and valleys of side-by-side tracks can also be well detected. The smoother surface with increasing laser power is also clearly visible, see right diagram. The monitoring system allows to decide how much material has to be removed during post-processing and whether the required layer thickness has been achieved. This saves time by avoiding intermediate or post-process control of the layer height, as well as material by adjusting the parameters during the process. With the accuracy of the sensor, its small distance to the process zone and robustness, it forms a solid basis for future closed-loop control approaches.

Another benefit is the simple installation of the sensor in the process setup compared to other measuring principles. While coaxial integration of OCT, pyrometers or cameras requires the optical elements to be adjusted and the systems to be calibrated, the triangulation sensor can simply be attached to existing optics. Furthermore, the wide lateral field of the triangulation sensor allows to record the valleys of a layer, which is not possible with a single point temperature or height measurement.

5. Conclusion

This paper presents an in-process monitoring system by using a new developed laser triangulation sensor from Falldorf Sensor GmbH which is well suited for LMD processes and provide a solid basis for a further control system.

- The in-process measurement shows a good agreement with the offline measurement by using a confocal microscope.
- Deep valleys and high peaks can be detected well during harsh environment, such as very low or high laser powers.
- With its wavelength of 405 nm and optical filters it is possible to measure the track geometry close to the process zone (10 mm).

Acknowledgements

The ZIM-project number KK 5274704KT1 was funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) via the German Federation of Industrial Research Associations (AiF) in accordance with the policy to support the Central Innovations of Medium-Sized Enterprises (ZIM) based on a decision by the German Bundestag and the Swedish governmental agency for innovation systems (Vinnova). Furthermore, the authors gratefully acknowledge the collaboration with the members of the project affiliated committee regarding the support of knowledge, material and equipment over the course of the research. The “BIAS ID” numbers are part of the figures and allow the retraceability of the results with respect to the mandatory documentation required by the funding organization.

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