9th International Conference on
Photonic Technologies LANE 2016

Industrial Paper

Capillary depth measurement for process control

Friedhelm Dorsch[a], Wilrid Dubitzky[a,]*, Lukas Effing[a], Patrick Haug[a], Sven Plasswich[a]

[a]*TRUMPF Laser- und Systemtechnik GmbH, Johann-Maus-Str. 2, 71254 Ditzingen, Germany*

Abstract

Optical coherence tomography (OCT) is an imaging technique based on a white light interferometer. The technique can be adapted to laser welding applications measuring the capillary depth and closed-loop control of laser power or feed rate. A controlled constant weld depth allows running applications closer to their process limits, thus increasing the output performance per production cycle. It is also expected that the online measurement of the weld depth reduces the number of necessary destructive sample inspections. An essential premise is a reliable weld depth measurement independent from process and environmental factors. This work analyzes the influence of feed rate, laser power, beam diameter, and work piece material on the capillary depth measured using the OCT technique and explains the underlying effects.

Keywords: Optical coherence tomography; OCT; capillary depth; weld depth; keyhole

1. Introduction

Optical coherence tomography (OCT) is used in laser welding applications to measure the capillary depth. It is based on white light interferometer with a broadband light source emitting at different wavelengths and interfering at short coherence length [1]. The interference signal is analyzed by a spectrometer at many spectral channels simultaneously. The advantage compared to conventional time domain spectrometer is that it generates depth information within a single measurement and therefore can be used to measure the welding depth.

The capillary depth measurement is an estimate for the weld depth, the latter being measurable by sample inspections cutting the workpiece along the weld. A controlled constant weld depth allows running applications closer to their process limits, thus increasing the output performance per production cycle. It is also expected that the online measurement of the weld depth reduces the number of necessary destructive sample inspections. Furthermore, it also might bring advantage for car underbody welding applications, where post-process sealing is currently necessary for corrosion protection. A controlled weld depth possibly would avoid destroying the protective zinc coating of the underbody, thus reducing time for post-processing and save cost for sealing material.

An essential premise to achieve these goals is a reliable weld depth measurement independent from process and environmental factors. This work analyzes the influence of feed rate, laser power, beam diameter, and work piece material on the capillary depth measured using the OCT technique and explains the underlying effects.

2. The Methodology

The experiment was performed using a TruDisk 6001 and TruDisk 16002 solid state disk laser with a BEO D70 welding optics from TRUMPF and an IDM white light interferometer from Precitec [2]. The IDM samples the keyhole with 70 kHz within a depth measurement range of 10 mm. Both, the focusing lens and the collimation lens of the welding optics had focal lengths of 200 mm, resulting in an image scale of 1:1. The size of the laser spot was defined by the laser light cable diameter. The alignment of the interferometer probe beam relative to the keyhole was optimized for welding mild steel at 4 kW laser power and 5 m/min feed rate. Four measurement series were performed varying one parameter while keeping the others fixed (Table 1). The

* Corresponding author. Tel.: +49-7156-303-333-49 .
E-mail address: wilrid.dubitzky@de.trumpf.com

alignment of the interferometer probe beam was not re-adjusted during the measurement series ensuring the comparability of the series (Fig.1).

Table 1. Parameter sets of the four measurement series.

	Feed rate	Laser power	LLK Ø	Material
Series 1	1, 3, 5, 7, 9 m/min	4 kW	200 µm	mild steel
Series 2	5 m/min	0.5, 1, 2, 4, 6, 8 kW	200 µm	mild steel
Series 3	5 m/min	4 kW	100, 200, 400, 600 µm	mild steel
Series 4	5 m/min	4 kW	200 µm	mild, high-alloy, duplex steel, aluminum

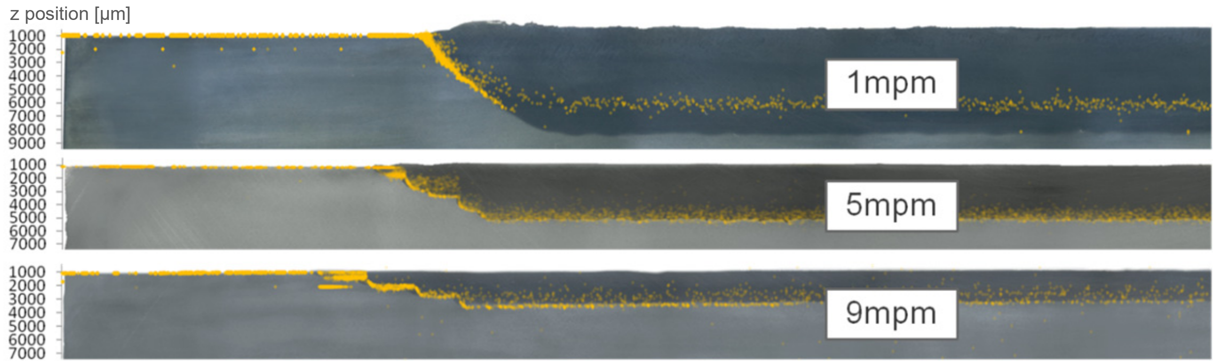

Fig. 1. Cross-section pictures and interferometer data (yellow points) at different feed rates. The workpiece surface was positioned at 1000 µm offset to achieve a safe reference for data collection even after a possible material deformation.

After welding, each workpiece was cut along its weld, polished, and etched. The weld depth was measured optically on the cross-section using a microscope. This depth was taken as reference for the depth measurement obtained from the interferometer. Fig. 1 shows an excerpt of the weld cross-sections together with the interferometric depth data.

The interferometric signal is processed in the OCT system and a Fast Fourier Transformation outputs a distance position. Because only light from the low-coherence length source shows the right wavelength and phase, light from other sources, as e.g. radiation from the welding process, does not contribute to the interferometer signal and all disturbing radiation is strongly suppressed. As the probe light intensity reflected from the keyhole is low, there is a significant amount of noise and erroneous signals which require filtering. The filtered distance values are plotted as histograms and fitted by Gaussian curves (Fig. 2). The keyhole depth is derived from the Gaussian curves, where the workpiece surface position at 1000 µm is taken into account and subtracted. Some distributions show a washed out shape or multi peak structure. This is a hint that the interferometer probe beam not only hits the deepest point in the keyhole but rather the keyhole front.

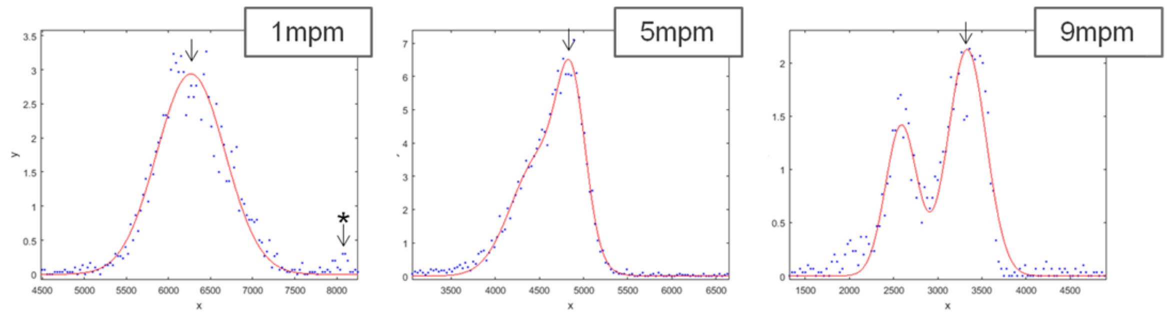

Fig. 2. Gaussian fits of the noise corrected interferometer data. The arrows mark the highest peak that has been used to determine the capillary depth.

3. Measurement results

3.1. Variation of the feed rate

Six welds have been performed on mild steel varying the feed rate from 1 to 9 meters per minute. The laser power of 4 kW and the laser light cable diameter of 200 µm were kept unchanged during this measurement series. The measurement at feed rate 9 m/min was repeated twice for process verification. The signal to noise ratio (SNR) was defined as quotient between the integral of the Gaussian curves and the constant noise level. The SNR is shown in Fig. 3a and is best at 5 m/min, the starting parameter for the alignment of the equipment. The capillary depth obtained from the interferometer and the depth obtained from the cross-sections match within 5% (Fig. 3b) with exception of one value measured at 1 m/min. At this lowest feed rate a double Gaussian peak structure of the signal leads to a wrong result when choosing the highest peak. The depth value obtained from the lower peak of the two Gaussians is marked by an asterisk in Fig. 3b. We assume that at feed rate 1 m/min the keyhole is long and narrow, and consequently the interferometer hits the keyhole front resulting in a wrong depth measurement.

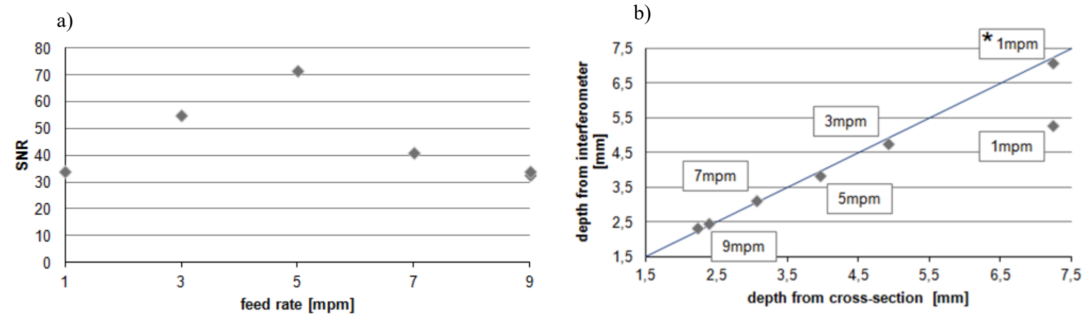

Fig. 3. a) Signal to noise ratio, and b) depth from the interferometer versus depth from the cross-sections.

3.2. Variation of the laser power

Six welds have been performed on mild steel increasing the laser power from 0.5 to 8 kW. The feed rate of 5 m/min and the laser light cable diameter of 200 µm were kept unchanged during this measurement series. The SNR decreases as a function of laser power (Fig. 4a). Again, the depths from the interferometer and cross-sections match quite well (Fig. 4b). For the lowest laser power of 500 W the measured interferometer peak is below the workpiece surface position at 1000 µm and thus the depth has a negative value. We assume that at such a low laser power a defined keyhole was not formed and that the signal from the interferometer stems from surface stray light.

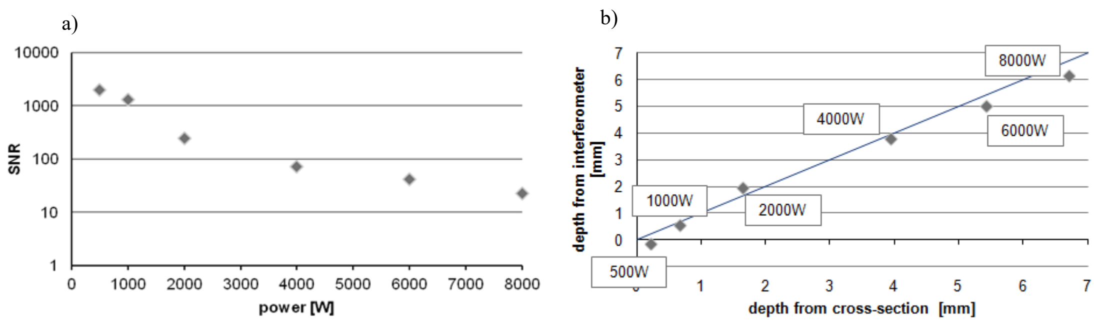

Fig. 4. a) Signal to noise ratio, and b) depth from the interferometer versus depth from the cross-sections.

3.3. Variation of the laser light cable diameter

Five welds have been performed on mild steel varying the laser light cable diameter from 100 to 600 µm. The feed rate of 5 m/min and the laser power of 4 kW were kept unchanged during this measurement series. The measurement using a laser light cable diameter of 600 µm was repeated twice for process verification. The SNR is best for a diameter between 200 and 400 µm (Fig. 5a). However, at 400 µm the double Gaussian peak structure of the depth signal leads to a wrong result if the highest peak is chosen (Fig. 5b). The result delivered by the lower peak is marked with an asterisk in the graph. We assume that the keyhole shape becomes too broad and the interferometer probe beam hits the keyhole edges. At 600 µm cable diameter the signal has almost vanished, as shown in the SNR.

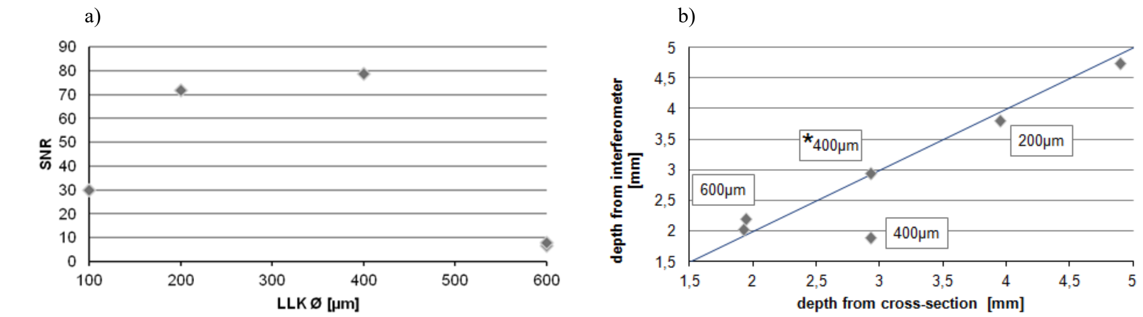

Fig. 5. a) Signal to noise ratio, and b) depth from the interferometer versus depth from the cross-sections.

3.4. Variations of the material type

Four welds have been performed on different materials. Mild steel, high-alloy steel (VA), duplex steel, and aluminum have been used. The laser power of 4 kW, the feed rate of 5 m/min, and the laser light cable diameter of 200 µm were kept constant during this measurement series. The signal to noise ratio is poor for aluminum due to the unstable keyhole (Fig. 6a). The best signal shows a perfect single Gaussian shape and is achieved with duplex steel, also showing the smallest depth deviation of 0.4% from the cross-section depth (Fig. 6b). Aluminum is known to have an unstable keyhole which is also reflected in the washed out signal shape. Still, the depth can be measured quite satisfactory.

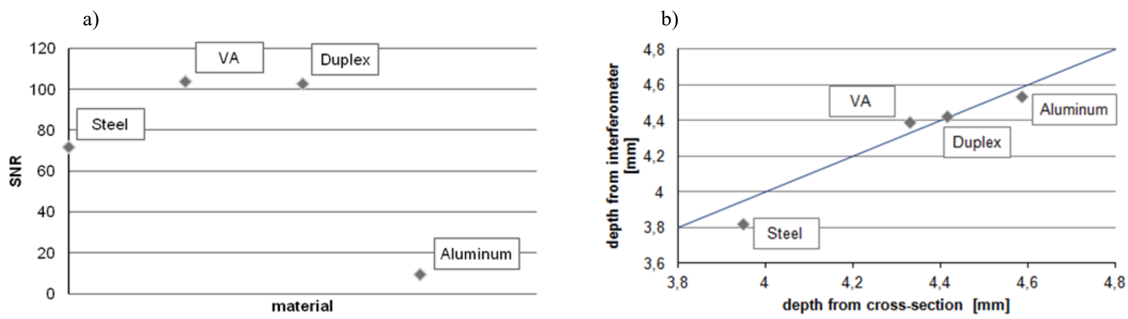

Fig. 6. a) Signal to noise ratio, and b) depth from the interferometer versus depth from the cross-sections.

4. Discussion

At typical powertrain laser welding parameters of 4 kW laser power, 5 m/min feed rate, and 200 µm laser light cable diameter (i.e. approximately 200 µm laser spot size), the OCT technique leads to acceptable results. Deviations between 0.4% (duplex steel) and 3% (mild steel) have been determined in respect to the cross-section depths for the different materials. It has to be noted that also the depths obtained from cross-sections are error prone. For instance, a wrong depth is obtained if the cross-section is not taken at the exact middle of the weld.

The multi Gaussian peaks in the signals at certain instances show the sensitivity of the measurement spot alignment in respect to the keyhole. If the keyholes shape changes, the deepest position is not hit by the interferometer probe beam anymore and realignment of the probe beam is necessary. The alignment should minimize the described effects of signal ambiguity. But manual alignment is time consuming. Thus, it is desirable to have automated self-aligning equipment that e.g. uses look-up-tables or functions in the parameter space of laser power, feed rate, spot size, and others.

Nonetheless, there are physical limits of the OCT technique for keyhole depth measurement (Fig. 7). This is especially the case at deep and narrow keyholes where the interferometer probe beam cannot hit the deepest point even at perfect alignment. At constant feed rate, this keyhole shape occurs at high laser power in combination with small laser spot size. Another limit is welding at low laser power density where a defined keyhole is not settling. At constant feed rate, this happens at low laser power combined with large laser spot size.

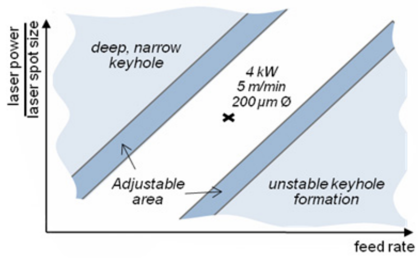

Fig. 7. The limits of the OCT technique in the parameter space.

Acknowledgements

We thank Precitec GmbH & Co. KG for the provision of the IDM to perform the measurements.

References

[1] P. J. L. Webster, et al., 2014. *Automatic laser welding and milling with in situ inline coherent imaging*. Opt. Lett. Vol. 39, No. 21, pp. 6217

[2] M. Kogel-Hollacher, M. Schoenleber, T. Bautze, 2014. *Inline Coherent Imaging of Laser Processing – a New Sensor Approach heading for Industrial Applications*. 8th International Conference on Photonic Technologies LANE