9th International Conference on
Photonic Technologies LANE 2016

Industrial Paper

Measurement and Closed-Loop Control of the Penetration Depth in Laser Materials Processing

M. Kogel-Hollacher[a,*], M. Schoenleber[b], T. Bautze[a], M. Strebel[a], R. Moser[a]

[a]*Precitec GmbH & Co. KG, Draisstrasse 1, 76571 Gaggenau, Germany*
[b]*Precitec Optronik GmbH, Schleussnerstrasse 54, 63263 Neu-Isenburg, Germany*

- Invited Paper-

Abstract

Since the moment when it was possible to achieve the necessary power density to start the process of deep penetration welding, accompanied by a keyhole, there is hope - and need - to measure the depth of this vapor channel. In the decades in which the technology of deep penetration welding has been used, various approaches have been developed that allow a message about the depth of the keyhole. All these approaches have one thing in common, the basics of determining the depth are based on secondary information, such as the dimension of the melt pool, or the strength of the emissions from the plasma or the metal vapor. Except by means of X-ray or destructive testing no method has been developed so far to determine the real keyhole depth. With the IDM system (In-Process Depth Meter) it is now possible to bring a system to market, which can measure the depth of the keyhole in industrial laser welding applications.

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Keyword: Low Coherence Interferometry, Process Monitoring, Quality Assurance, Penetration Depth Control

1. Introduction

The principle of online process monitoring is based on the observation of significant indicators describing the properties of the workpiece in the interaction zone and its adjacent area (Fig. 1). The technology for acquisition and processing these indicators is useful only if it can respond clearly to a significant change of the process conditions or the resulting quality. Process control systems must operate in a contactless manner, so that they exert no adverse influence on the interaction zone. In laser material processing this requirement is not a problem, because the processes are accompanied by a number of effects that can easily and reliably be observed from a distance.00

* Corresponding author. Tel.: +49-6102-3676-133 .
E-mail address: mkh@precitec.de

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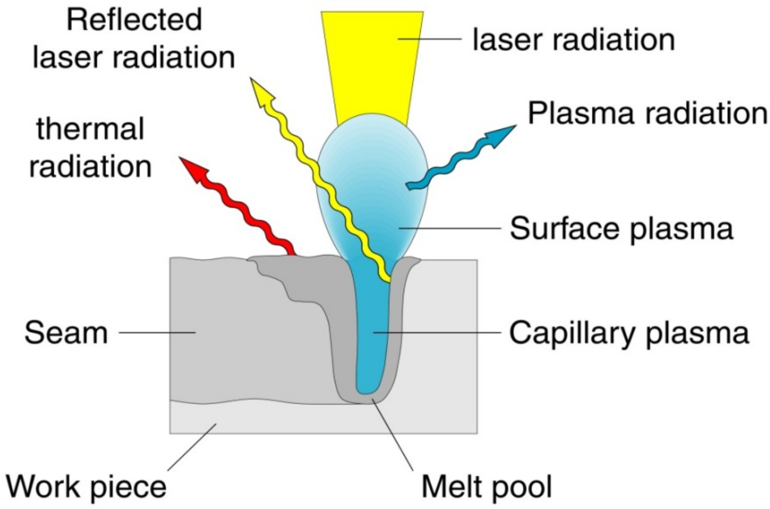

Fig. 1. Overview of the electromagnetic emissions during laser beam welding.

Process monitoring devices for laser processing usually make use of the radiation emission of the interaction zone, which is detected by simple photodiodes or radiation pyrometers. 000 Information about the molten zone is collected in the VIS (visible light spectrum) and in the short IR region (infrared spectrum). Information about plasmas or of the luminance of the metal vapour is primarily obtained in the VIS and UV (ultra violet) range of the electromagnetic spectrum. To gain an insight about the actual condition of the process from the measurement data, the monitoring systems have to be trained and optimized for each new component. The optimization procedure can be carried out through systematic learning-based approaches such as expert systems or by artificial neural networks. The disadvantage of this method is that the process monitoring device has to be adjusted and recalibrated for each application. When Multi-Sensor systems are used, which are based on the correlation of different measurements (e.g. UV, IR and reflected laser radiation), the large amounts of data produced delays the reaction time of a closed loop system. The main deficit of technology based on traditional measuring sensors is, however, that in many cases there is no clear correlation between the measured intensities and the quality of the eventual product.

The missing relationship between the measurements and the process can be almost fully compensated for by the use of imaging sensors and camera technology 0000. With camera-based detectors a spatially resolved detection of the interaction zone and the adjacent areas can be carried out. Information on the process can thereby be detected, which remains hidden to integral measuring sensors. Depending on the application, this information can also be used to real-time control a process.

2. The IDM measuring principle – Low-coherence interferometry in laser materials processing

OCT technology (Optical Coherence Tomography) is an imaging technique based on low-coherence interferometry (LCI). It is a long established medical examination procedure. An interferometer with a light source of low coherence length is used to measure distances and the composition of human tissue, e.g. the cornea. This method compares the length of a measuring path to that of a reference path in an interferometer. The short coherence length is achieved through the use of light sources that emit broad spectrum light. The applied light sources are typically super luminescent diodes (SLDs) with a range of some 10 nanometers, or a Swept Source Laser. In 2006, Precitec Optronik GmbH launched a thickness and distance sensor based on spectral domain OCT and this was adapted to material processing applications with laser sources of high beam quality. The adapted technology allowed distance measurement to the required accuracy of about 10 microns, even over long distances.

However, the real innovation and thus the basis of a technological leap in the field of process monitoring/control is the fact that the accuracy of the interferometric measurement is not affected by the electromagnetic emissions from the vapour capillary or the adjacent areas.

The intensely bright emissions caused by the high power beam material interaction are not coherent with the light emitted by the low coherent light source of the measuring system and thus only the measurement system light is involved in interference between the reference and the measuring path. Based on an accurate adjustment of the measurement beam coaxial to the processing laser, this technology for the first time provided an exact measurement of the depth of the keyhole, independent from seam geometry or processed material. The only restriction is in the dimension of the measurement point compared to the spot size of the processing beam and the measuring range in the axial direction. The currently implemented commercial system IDM developed and supplied by Precitec has a measurement point diameter of 50 µm and a measuring range of 10mm.

A very good example of the extraordinary functionality of the measurement method is demonstrated in the signal behaviour during welding an overlap joint of zinc coated steel, a typical joint geometry in automotive industry. (see Fig. 2).

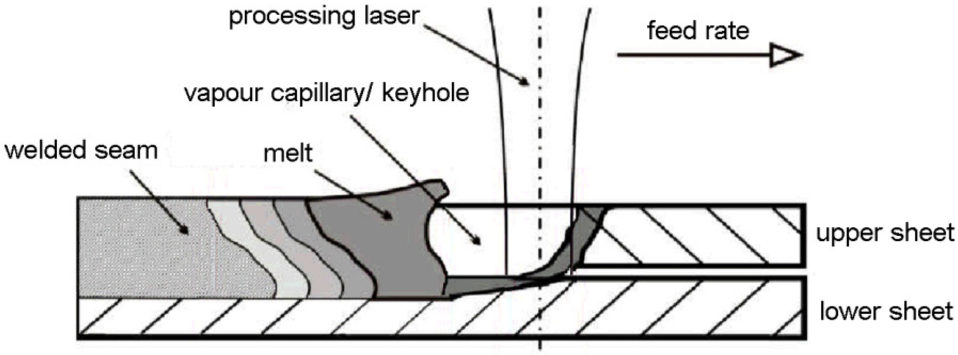

Fig. 2. Schematic figure of an overlap weld joint configuration with gap.

Since these plates are coated with a zinc anti-corrosion layer, for weld quality reasons a gap of 0.1 mm must be strictly adhered to in order to let zinc vapour escape from the weld zone.

Using a feed rate of 3m/min, a spot diameter of 400 µm and a linear increase of the laser power, a significant variation in the depth of penetration can be achieved. This experiment leads to a variation of the penetration depth, starting at low power with heat conduction welding, then partial and full penetration of the top sheet, reaching the gap position in the intermediate area, penetrating the bottom sheet and finally nearly full penetration before the laser is switched off again. The transfer phase from fully penetrating the top sheet to starting to process on the bottom sheet can clearly be seen in the measured data. Thus this seam geometry is perfectly suitable to determine the performance of this process monitoring technology.

The complete signal curve for the seam geometry is shown in Fig. 3, the raw data generated by the measuring system is shown, before the statistics module in the software is applied.

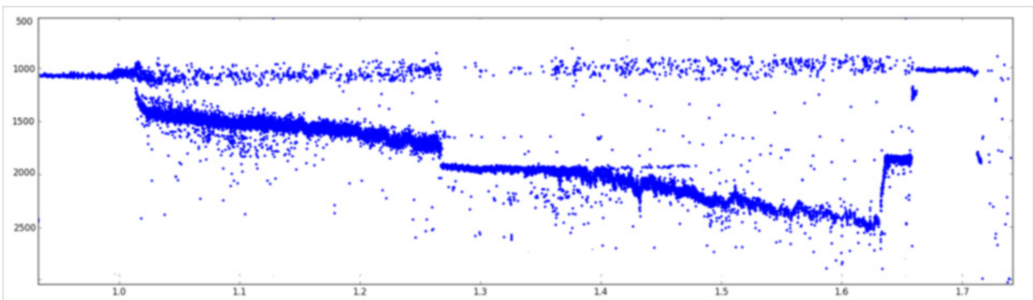

Fig. 3. Raw signals of the measuring system during welding of an overlap weld joint applying a power ramp.

Two essential pieces of information can be derived from this figure. First, the scattering of the raw data is extremely low, meaning a precise indication of the depth of the ground of the keyhole can be derived even without the statistics module. Second, parallel to the signal of the depth a clear measurement of the top sheet surface is possible (Fig. 3, value at 1000µm). Having realised this it is obvious that a value of the keyhole depth can be derived independently of the stand-off distance of the processing head. The precise depth value is just a result of a subtraction of two values.

Another example is demonstrated in the following figure:

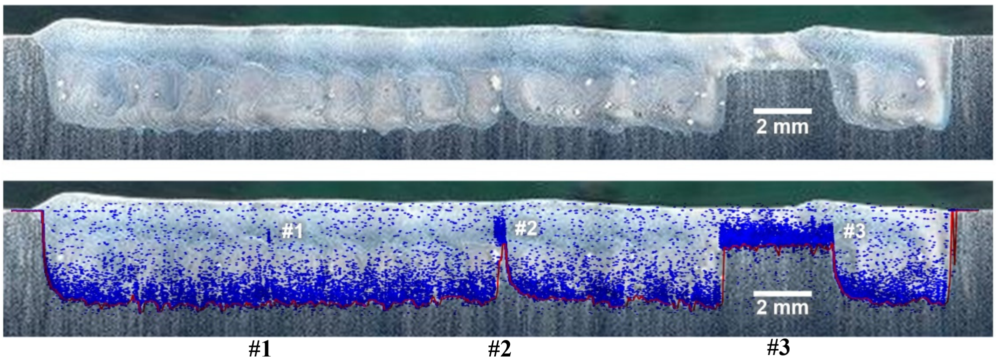

Fig. 4. Example: automated signal extraction for a weld stainless steel and three intentional interruptions of the laser power (#1: 1 ms; #2: 10 ms; #3; 100 ms).

To confirm that the measured data exactly display the variation of the keyhole depth, the longitudinal cross section must be examined. The characteristics in these trials are the 3 short interruptions by reducing the laser power for #1 – 1ms, #2 – 10ms and #3 – 100ms. The inertia of the process is so high that a 1ms interruption does not result in a penetration depth variation, but the 10ms and 100ms ‘reduced laser power’ events are clearly seen in the cross section and in the measurements.

At this point in the description it makes sense to talk about the relationship between the raw data and the derived depth values. It is obvious that, due to the amount of data involved, a statistical analysis tool is necessary. The high acquisition rate of 70.000 measurements per second is most helpful, because the use of a moving window with an averaging of the measurements increases the robustness of the exact depth measurement. One has to keep in mind that every value taken from the process and displayed in the graph is an exact measurement, e.g. from front wall of the keyhole or from spatter emerging from the interaction zone. The red line in Fig. 4. Example: automated signal extraction for a weld stainless steel and three intentional interruptions of the laser power (#1: 1 ms; #2: 10 ms; #3; 100 ms). is the result of the data processing and proved to exactly follow the capillary depth and could be used as part of a closed loop control system.

3. From measurement to control

In situ measurement of the depth of the vapour capillary in laser material processing facilitates the generation of a closed loop for a precise control of this process variable.

The following figures show an example of penetration depth control. Compared to previous approaches in closed loop process control, the controlled variable is explicitly the depth of the capillary. In the relatively simple control loop the obvious control value is the laser power, thus an extremely flexible interface is provided, compatible to more or less all laser sources.

The process input variables for the demonstration of welding control in this example are:

Laser spot diameter: 400 µm, welding speed: 3m / min, material: steel, measurement frequency: 70 kHz, control frequency: 1kHz

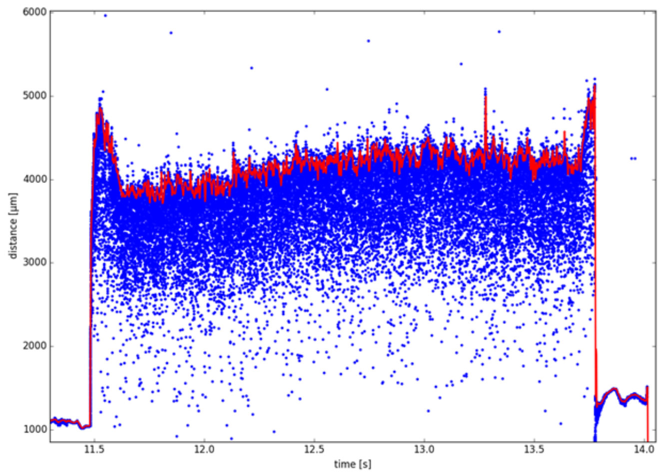

Fig. 4. Uncontrolled process, laser power 2,2 kW.

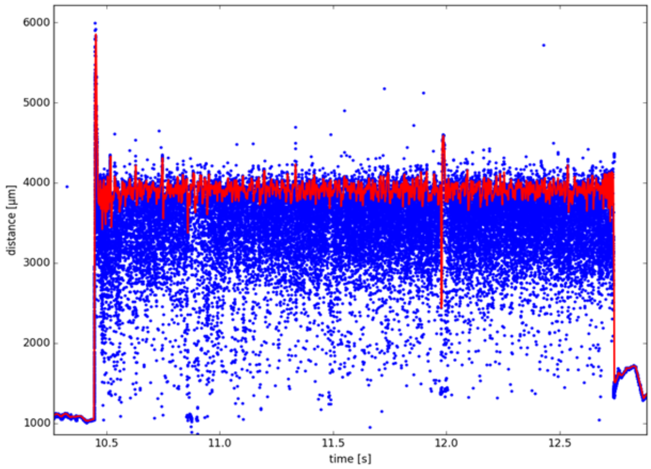

Fig. 5. Controlled process: Setpoint 3 mm penetration depth.

The following application example is proving the control capability of the sensor welding zinc coated steel (DX54) in overlap joint configuration with 0.1mm gap between the sheets. This material is intensively used in automotive applications and therefore important to be investigated. The process input parameters applied are those which can be found in the majority of the industrial applications, focal distance 200mm, spot size 200µm. As the sheet thickness is 1.5mm the idea was to perform a controlled partial penetration weld with a target depth of 2.7mm, which results in 1.1mm penetration into the lower sheet. As the speed was varied stepwise from 2m/min. to 6m/min. the control signal to the laser source had to increase the laser power with increasing speed.

In Fig. 6 the result of the tests for one welding process is shown. The requested penetration depth (top graph) is kept constant at 2.7mm and by varying the process speed the output signal is automatically stepwise increased (bottom graph).

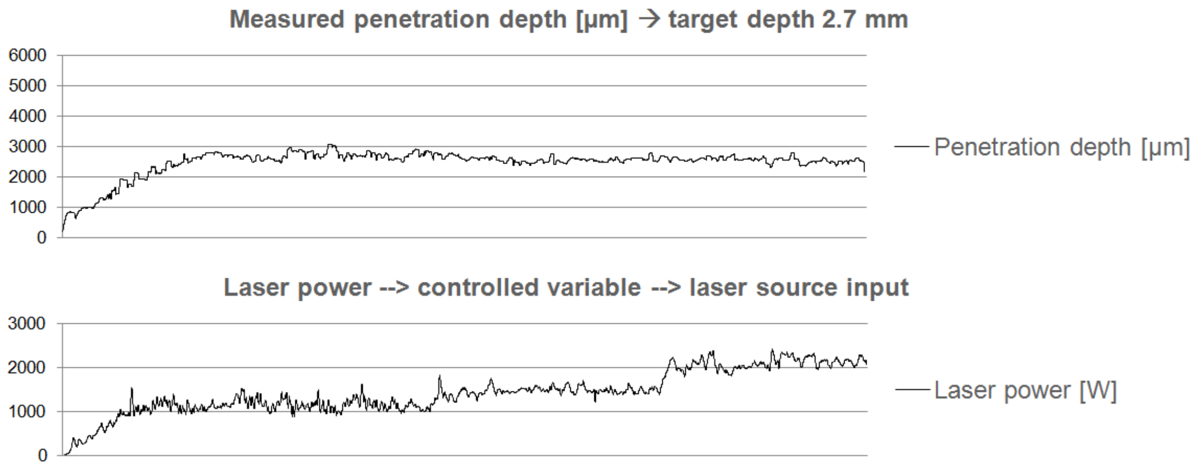

Fig. 6. Measured penetration depth (top) and control signal to the laser source (bottom).

The corresponding photos from top- and backside of the weld samples are shown in Fig. 7. It is clearly to be seen, that the full penetration situation could be avoided.

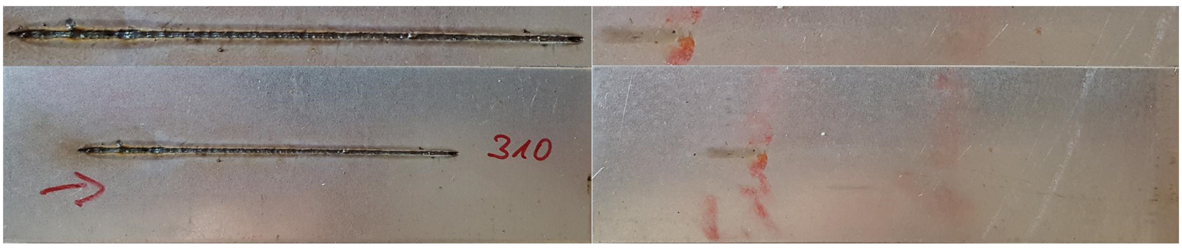

Fig. 7. Top- and backside of the depth controlled weld.

4. Industrial implementation

Based on the numerous findings the industrial application of the new measurement technology was implemented in a way that made an easy adaptation to commercial laser welding processing heads possible. The resulting IDM (In-Process Depth Meter) system is presented in the following figure.

Fig. 8 shows all components of the IDM system. The central unit can be seen in the lower right of the picture. On the one hand the system is a self-contained unit. With an appropriate parameterization the output value "Keyhole-depth" can be obtained and this value can be fed directly to a machine control unit. With standardized interfaces this system can be incorporated into a large-scale monitoring strategy. In this case, it is an add-on to other systems for complete validation of the required seam and component quality.

A remarkable feature of the IDM system in addition to its compactness, that, starting from the processing unit, the light is completely fibre-guided. This facilitates integration into an industrial environment, as the risk of contamination of optical components is very low. The length of the fibre between the evaluation unit and the processing head is almost arbitrary, typical distances found in industrial applications can be easily bridged.

The mechanical interface of the optical fibre allows an accurate lateral adjustment of the measurement point. An additional adjusting unit can shift the measuring spot in the axial direction. To further adapt the signal quality the free aperture can be modified. Thus, an adjustment in all degrees of freedom is possible, and this offers the possibility to interface the system to all typical cw laser welding head configurations. However, for the best possible signal yield, it is important that all optical components in the beam path are optimized for the measuring system’s wavelength.

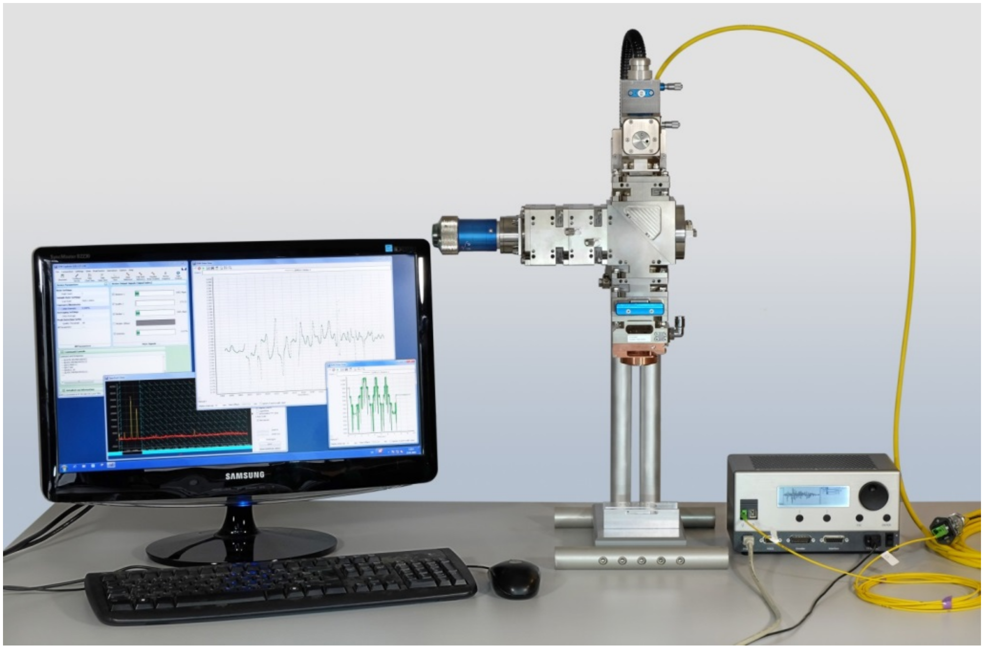

Fig. 8. IDM sensor system adapted to a commercially available laser welding head.

5. Conclusion

This innovative measuring principle for the first time allows in-situ measurement of the keyhole depth during laser processing. Previously available sensor systems need to rely on an understanding of physical dependencies between the detected information and its data processing to derive an estimation of the essential process parameter “penetration depth”. With the IDM system a real value with micrometer accuracy is displayed. The accuracy of the measurement depends on various process input variables, including the spot diameter of the processing laser, welding speed, material and, last but not least, the accuracy of the position of the measuring point with respect to the keyhole position. Results show an accuracy of the measured value of better than +/- 10 microns in typical process windows. This is a definite improvement to the state of the art in process monitoring because it is a real measurement.

Acknowledgements

Some of the work on the development of the system was carried out within the framework of three public funded joint projects. At this point the company Precitec Optronik GmbH would like to thank the project executing organisation VDI-TZ and KIT, also the Federal Ministry of Education and Research for their support.

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