Keyhole Depth is just a Distance

The IDM sensor improves laser welding processes

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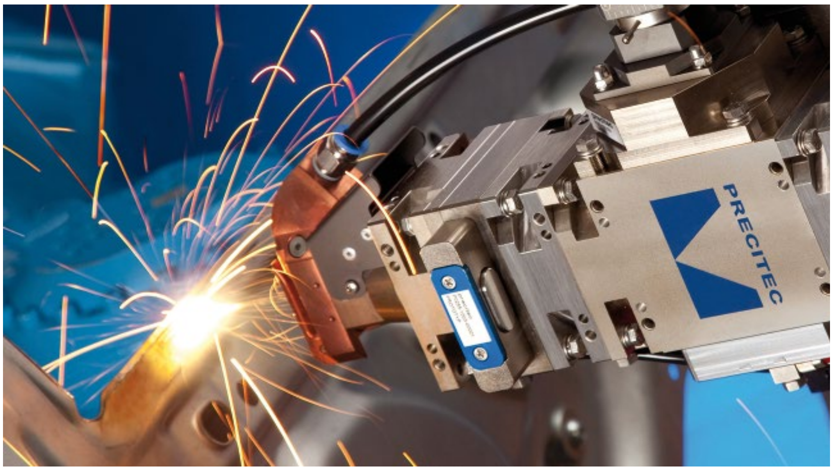
Talking about laser welding predominately means talking about the generation of a keyhole, the physics behind and invariably the depth of this steam capillary. Having the ability to measure this depth would undoubtedly raise the confidence in laser welding and also raise the quality of the processed part on a higher level.



With the IDM (In-Process Depth Meter), Precitec developed a sensor system that is able to measure the depth of the keyhole in-process. On the basis of low-coherence interferometry, with a high robustness of the measured values against process emissions, the system is perfectly qualified to provide the measurement that the industry has been asking about for decades.

As a leading manufacturer of processing heads, Precitec is able to provide a solution that is easy to integrate into existing optics. As a leading manufacturer of non-contact measurement systems, the company is also able to reduce the hardware to the most compact size. Both have proven their industrial suitability in hundreds of applications.

A substantial reason for the increasing use of the laser in numerous fields of industrial production is the increased efficiency in comparison with competing techniques. Another reason would be the unique features of the laser beam as a tool itself. To really gain a profit by the use of this tool, a highly automated quality control of the production process is needed.

The laser welding process offers several possibilities for process monitoring systems or process control but the complexity of the laser process itself, meaning the dependence of the processing result on several process input parameters, does not facilitate their use.

As only continuous supervision of the manufacturing process can guarantee the high demands on the quality of the produced parts, process monitoring systems have become more and more standardized devices in laser applications. There is no doubt that the basis for reliable on-line process monitoring systems is the possibility to measure significant indicators, which demonstrates the instantaneous condition of the interaction zone and/or neighbouring areas.

One of the most significant pieces of information that needs to be measured in order to qualify the strength of the weld with respect to mechanical load and stress is the depth of the keyhole. There have been numerous approaches to find a sensor technology to be best placed to discover a correlation between the keyhole depth and the measured signal. These attempts have been discussed extensively in R&D and some have found their way to industrial applications. The common feature of these solutions is that they need basic understanding of the beam-material-interaction to correlate the signal with the quality criteria. These systems provide an estimate and not the actual keyhole depth.

The IDM system is able to really measure the depth of the keyhole. The technology and the comparison between existing sensor systems and application results will be content of the following article.

Results of laboratory and application trials

The basic measuring principle of the IDM sensor allows the user to measure the distance to any kind of surface with a high axial and lateral resolution. Thus it is basically independent from the process parameters and can measure the welding depth of any process, as long as a keyhole is present. Nevertheless, the properties of the keyhole may have an impact on the quality of the measuring signal. Therefore the IDM is continuously tested on a variety of applications to prove its functionality. The ability to measure the depth of the keyhole was tested up to 9 mm of penetration depth and up to 20 m/min processing speed.

An exemplary examination is the overlap weld of metal sheets as can be

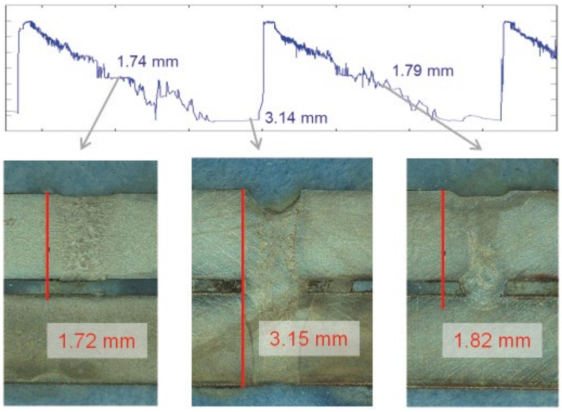


Fig. 1 Measured penetration (blue curve) and results from sections; the saw tooth led to a variation of the penetration depth in the overlap weld of galvanized steel.

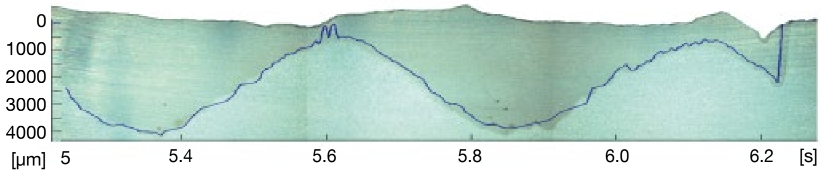


Fig. 2 Section of a laser welded workpiece with a sine-modulated laser power. At low power, the keyhole collapses, leading to unsteady measuring signals of the penetration depth.

found in body-in-white applications. A 1.5 mm sheet of galvanized steel H340LAD and a 1.5 mm sheet of boron steel 22MnB5, separated by a gap of 0.1–0.2 mm are welded together at 3 m/min by means of a fiber laser. In order to simulate a variation of the penetration depth, the laser power was modulated between 400 and 2800 W with a saw tooth-signal at 1.5 Hz. Fig. 1 shows three different cross sections compared with the online IDM-result. The main message is, the IDM signal can be used to accurately determine the properties of the welding process; in the case of values close or below to 1.7 mm, no keyhole is present in the lower work piece. IDM values between 1.7 and 3.1 mm prove the penetration in the lower work piece, whereas values above 3.1 mm may result from a full-penetration. In case of a through penetration, the ratio of reflected measuring light from the bottom of the keyhole decreases, further allowing the detection of the through-penetration.

Fig. 2 shows an superposition of a filtered IDM signal and a longitudinal section of a weld in 5 mm thick mild steel. The laser power was modulated with a sinus-shaped-signal. Slight differences between the measured depth and the cross section are due to a discrepancy between the actual center of the weld and the obtained section. One can note the collapsing keyhole for very small penetration depths, leading to a non-continuous depth signal. Heat conduction welding has no keyhole and as such, the depth of the weld cannot be measured. Here again, the IDM signal can be used for accurate measurements of the keyhole depth. In combination with the Laser Welding Monitor (LWM) platform, the smallest deviations from the reference depth are detected. Another use of the IDM signal is the set-up of the laser power profile for welds with varying parameters, such as velocity, material properties or focal shift. By analyzing the IDM signal, corrections can be made on the laser program in order to obtain a constant penetration depth. The closed-loop control of the welding depth is in sight.

In order to prove the accuracy of the measurement signal, trials with simultaneous acquisition of IDM signals and X-ray images were performed at the Institut für Strahlwerkzeuge (IFSW) in Stuttgart. These trials consist of welding into the front side of work pieces with a thickness of only a few millimeters, in order to allow X-ray measurements. The outcome of these is a set of IDM-signals paired with high-speed videos of a lateral scan of the keyhole. The analysis of these videos does not only reveal the absolute depth of the keyhole, but also its fluctuation in length, width and constancy of its shape. Fig. 3 illustrates the course of the IDM signal and the online X-ray measurement of the keyhole. The lower end of the keyhole is hard to distinguish from the rest of the work piece. Due to its minimal diameter at the end, the contrast of the X-ray image is reduced to a minimum.

No doubt, in-process monitoring systems as the combination of IDM and LWM are useful in production environments, where the repeatability of the welding process is given.

Fig. 4 shows the IDM-signals for a laser welding process on galvanized steel, a material typically used in body-in-white applications. The process (a) suffers of a high fluctuation of the laser power at the workpiece surface due to absorption and scattering in the metal fumes. This is why the keyhole depth is strongly varying, leading to an irregular seam quality and insufficient penetration depth. This can easily be seen in the keyhole signal. Process (b) uses an optimized set-up allowing to obtain a stable keyhole depth. Short deviations of the optimal keyhole depth, which occurs two times in this workpiece, can now be monitored.

The field of application is large for the IDM sensor. It can be used as a tool to understand and optimize laser welding processes. Once the optimum pro-

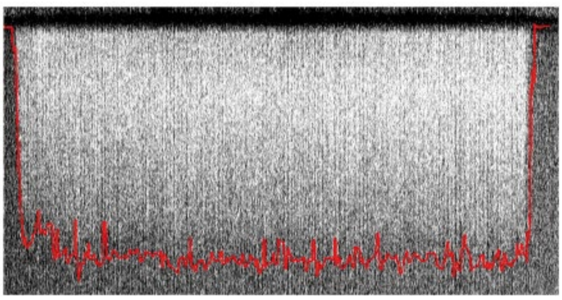


Fig. 3 X-ray image of a keyhole with superimposed IDM signal (Source: IFSW Stuttgart).

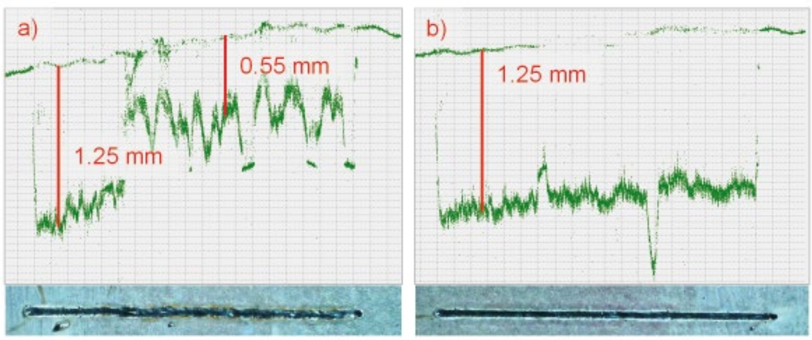


Fig. 4 Comparison of IDM signals for an unstable keyhole (a) and stable keyhole (b), resulting in a continuous seam geometry.

cess window is set-up, the IDM is used to track the keyhole depth, capable to monitor the process with an accuracy never reached before.

Process monitoring today

The principle of on-line process monitoring in laser welding is based on the acquisition of some indicators that describe the current condition of the work piece in the interaction zone and its adjacent areas.

One indicator is applicable for monitoring purposes if it is directly coupled with a significant change of the process situation and the resulting quality. Further on, process monitoring systems must operate contact-free so that there is no disturbing influence on the interaction zone. This requirement is typically not a problem in laser material processing, since this process is accompanied by a number of effects that are reliably observable from the distance.

The measured quality indicators are usually captured out of the electromagnetic radiation emitted from the processing zone and they are measured by simple photodiodes or pyrometers. To evaluate the actual condition of the process, the sensor systems must be gradually established and optimized for each new application. The optimization can be achieved through systematic learning-based approaches, such as expert systems or artificial neural networks. A disadvantage of this procedure is that for each new application the settings for an operative process monitoring system must be adapted by time-consuming, successive approximation. Furthermore, these solutions are highly sensitive to changing material or system input parameters. The deficit of the system technology based on integral measuring sensors, however, is that in many cases no clear correlation between the captured signal intensity and the existing process disturbances is given, respectively the clear inference of detected intensity and resulting weld seam property is missing.

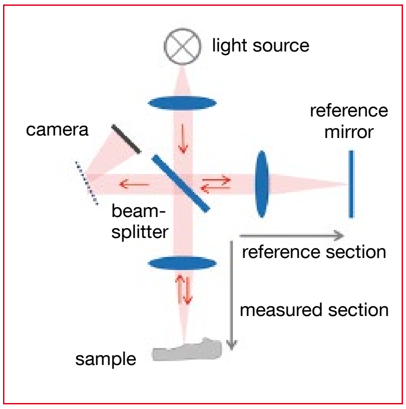


Fig. 5 Basic principle of low coherence interferometry; the difference between the reference and the measured section leads to a signal modulation captured by an image sensor.

This deficit can partly be compensated with imaging sensors and camera technology. With camera-based detectors, a spatially resolved detection of the interaction zone and the adjacent areas is carried out and information about the machining process is acquired, which remains hidden from the integral sensors. Ideally a classification, and in some conditions even a deterministic statement about the process condition can be generated. Depending on the application this process information can also be used for control.

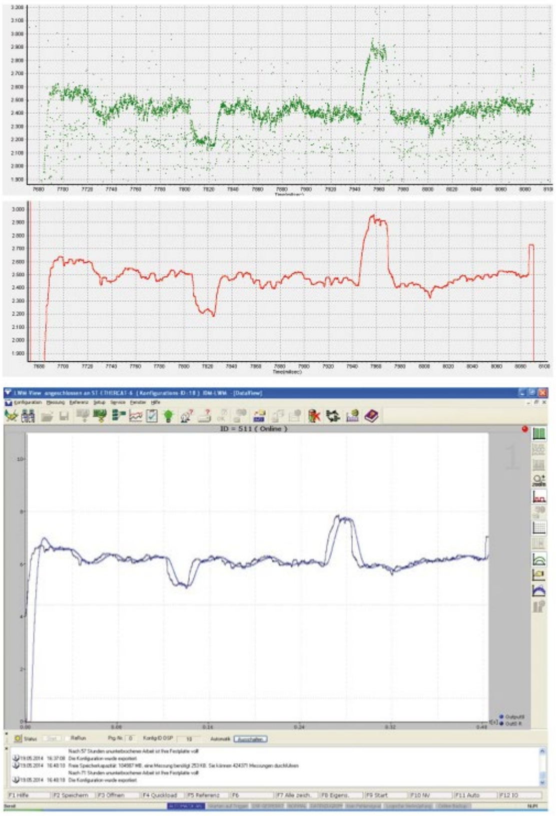


Fig. 6 Representation of different signal states of the IDM: the first figure illustrates raw data, whereas the second figure shows the output of the IDM. The last figure displays the measured signal within the LWM.

The IDM measuring principle

The IDM technology is an imaging method based on the low coherence interferometry (Fig. 5). In medical examinations optical coherence tomography has been established for years. The light of low coherence length with the aid of an interferometer is used for distance measurement of scattering materials like human tissue. This method compares the distance of the reflections of the measurement beam directed towards the measuring object with that of a reference beam in an interferometer, typically build as Michelson interferometer. The short coherence length is achieved by the use of light sources that emit spectrally wide light.

Besides all the effort in mechanical and optical integration of the sensor components, the real innovation achieved with the adapted technology is as follows; the accuracy of the interferometric measurement is not affected by electromagnetic emissions from the vapor capillary or their adjacent areas, neither in deep penetration welding nor during laser surface modification. Only the “own” light emitted from low coherent light sources leads to interference between the reference and the measurement path. Thus with accurate positioning of the measuring point, a measurement of the depth of the keyhole is possible coaxially to the processing laser regardless of weld geometry and material. The topography of a structured surface can be exactly determined independent of the surface condition. The only limitation is the dimension of the measurement point relative to the spot size of the laser processing and the size of the measurement range in the axial direction.

The IDM sensor

The development of the IDM sensor first started with lab-trials in the year 2007. The set-up allowed to measure seam geometries through a welding head with a focal length of 680 mm. In the years that followed, different fields of application were evaluated against technological feasibility and market demands. The decision to measure the penetration depth was made at an early stage, reflecting the permanent need for more accurate in-process sensors. As such, Precitec revealed its IDM sensor in the year 2013. Since then, the system is introduced in different laser welding applications. The innovative sensor design and its usability were awarded with the second price of the Innovation Award Laser Technology 2014.

The sensor unit provides the connections to the welding head and offers a variety of interfaces. The RS422 connection is used for real-time data transmission from and to the IDM sensor, e. g. with other sensorial equipment or a higher-level controller. At the same time, the network connection can be used to connect a Windows computer running the IDM software, called IDM explorer. Additional connections are made available for trigger, synchronization and analog output of measuring results.

The collimation unit on the welding head is used to adjust the measuring light into the keyhole. The integrated x/y-displacement is required to perfectly hit the center of the keyhole.

In order to deal with the large variety of possible keyhole signals, the real-time data processing is kept flexible. Starting with the raw measurement data, different filters are offered that can be combined. All states of the signal can be visualized and saved through the IDM Explorer.

The full performance of the IDM is revealed in combination with the LWM. Ordinarily used in combination with photodiodes, the LWM can also integrate the IDM, allowing the use of the same error detection on photodiodes and the IDM. This solution offers the biggest comfort for end-users, as it completely integrates the IDM hardware into the LWM control cabinet. A direct access to the IDM sensor is only required during the set-up of the process monitoring. Once installed, the LWM remains the single interface for the PLC or the machine operator.

LWM’s error detection relies on the comparison of measured data with predefined signal envelopes. By analyzing the IDM signal, too high or too low penetration depths can be detected. A further variance analysis of the penetration depth allows the detection of unstable processes or other discontinuities of the keyhole-geometry. In combination with the recorded process emissions from the photodiodes, a comprehensive in-process monitoring for laser welding applications is offered. Fig. 6 depicts the acquired raw data (green measurement points) from a process with short fluctuations of the penetration depth. The red curve is the output of the IDM sensor that is forwarded to the LWM system. Once inside the LWM, it can be further processed and used for classification.

Company

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The company is a specialist supplier of highly sophisticated laser systems for material processing. For laser joining Precitec offers processing heads and automated quality control systems as all-in-one complete integrated packages. Before the welding process high resolution cameras detect the position and geometry of the joint by using triangulation principle and grey scale value analysis to move the welding head to the exact point. In-process sensors and cameras then provide information on the welding process stability and any welding defects. Post-process cameras measure the geometry and the surface of the seam.

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Conclusion

The IDM sensor itself is just a device to measure a distance. But due to its high spatial and temporal resolution and its robustness against process emissions, it is the perfect tool for the extremely difficult environment of laser material processing applications. The measurement of the real depth of the keyhole is a new dimension in the field of process monitoring. Finally, the quality assessment of laser welded parts is based on geometrical measurements and not a correlation between process radiation and the welding result. In combination with the LWM, the IDM is a ready to use sensor for production environments.

The technology itself also leads to a redesign of sensors currently used in the field of laser processing. New applications are made available for the laser welding process, thus strengthening the position of the laser as a tool for production and research.

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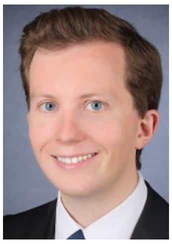

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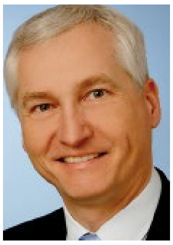
works as product manager for Precitec GmbH & Co. KG. Before joining Precitec in 2010, he studied electrical engineering at the University of Karlsruhe and completed his studies at the Technical University of Munich. There he worked in the field of data processing for laser applications. At Precitec he started with R&D-projects and became team leader in the systems development department. Nowadays, his focus lays on laser welding and process monitoring solutions.



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began his activities in the area of lasers while working for his MS degree (RWTH Aachen University, Germany) at the Fraunhofer Institute for Laser Technology in 1994. In 1996 he joined Precitec Optronik GmbH. In 2008 he obtained his Ph.D. at the Technical University of Berlin, Germany.
In his position as head of the department R&D projects he oversees governmentally funded projects. At present, he is a member of the board of directors at the LIA and earned the 3rd place in the Innovation Award Laser Technology in 2012 and the 2nd place in 2014.

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