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Laser integrated process monitoring

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Abstract

In many material processing applications the detection of process emission is the basis for process monitoring, reliable process control and quality control systems. Coherents laser integrated process monitoring system (HighLight SQD) detects back reflected laser power and visible process light (plasma). The sensors are placed inside the process fiber connector of the high power fiber laser and ensure a high quality signal detection due to a high signal to noise ratio and a measurement coaxial to laser beam. A wide range of applications benefit from the availability of these signals. For cutting processes, events like piercing end, cut interruption and self-burning can be detected. Decreased cut quality like burr formation and plasma-cut is observable as well. For hairpin welding applications, failure detection is possible as misalignments like height offset, gap, v-gap or lateral offset are visible in the process monitoring signals.

Keywords: process monitoring; fiber laser; cutting; welding; HighLight SQD; HighLight FL

1. Introduction

Process monitoring has become a standard in industrial processing and gets more and more important following the trend to "Industry 4.0" and the automatization of production lines, incl. the need to control the manufacturing processes and the quality of the products.

A wide range of sensor technologies exists in a variety of process monitoring systems [You, 2013]. Sensors that are used today for process monitoring are typically integrated into the processing optics by the use of

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dichroic mirrors or other optical elements which can cause change in specifications of the process head, add weight and/or increase its size, which increases the required space. Additionally, sensors can be integrated into the laser beam switch or into the laser cabinet, which is located farther from the process zone. Consequently, the signal is affected and attenuated by all optical elements in the optical chain, with the potential to cause errors. Non-coaxial measurements can be located close to the process zone but depend on angle of incident of process light, therefore the setup is difficult to install and the repeat accuracy is low. Optical coherence tomography is a relatively new process monitoring tool and is able to deliver information even about the welding depth [Bautze, 2015]. Nevertheless, these are expensive and complex measurement setups with significant extended investment costs.

Many industrial applications rely on photodiode based process monitoring systems as installation and handling is relatively simple [Norman, 2007]. A further simplification is made by implementing these sensors directly into the process fiber connector [Blomster, 2012]. The benefit of the resulting laser integrated process monitoring solution is clearly the easy use and implementation into laser machining systems without the need to add extra optical components or additional sensors to the beam guide system. The setup is compatible with all process head configurations including scanners.

This paper illustrates the variety of applications which benefit from a laser integrated process monitoring system close to the process zone, coaxial to laser beam. A high signal to noise ratio as well as the high resolution of the signals offers a broad field of applications. The following chapter describes the setup and the principal functionality of the laser integrated process monitoring system. The subsequent part explains the value of the signals in cutting applications regarding piercing-end detection, cut interruption detection and cut quality measurement. Last but not least, welding applications demonstrating the significance of the signals for failure detection exemplary shown on 0.8 mm zinc coated mild steel and copper hairpins is described. Finally the results are summarized and an outlook to upcoming solutions for signal analysis is given.

2. Setup Laser Integrated Process Monitoring

Laser integrated process monitoring is available for all lasers of the high power fiber laser series HighLight FL. A typical setup is shown in Fig. 1. Three sensor signals are available at the customer laser interface. The monitoring system consists of a sensor inside the fiber laser cabinet measuring the laser power as well as process sensors inside the QD process fiber connector enabling the detection of back reflected laser power and process emissions within the visible spectral range like shown in detailed drawing of Fig. 1.

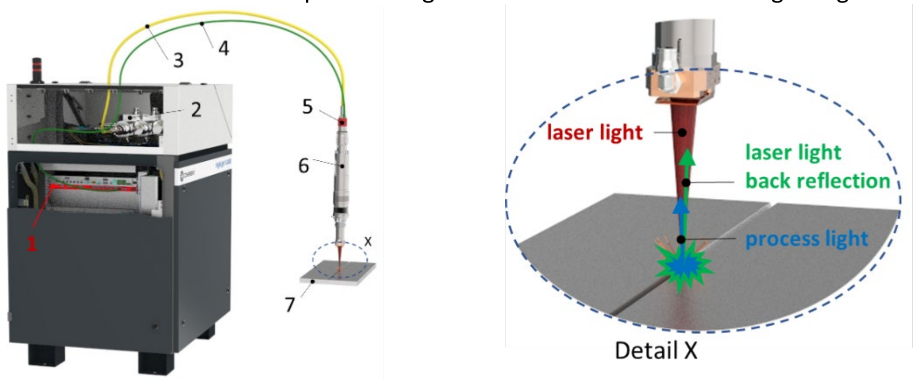


Fig.1. Setup laser integrated process monitoring; 1. Process Monitoring Board, 2. Fiber-Fiber-Switch, 3. Optical fiber, 4. Power & communication cable, 5. Special QD fiber connector measuring visible process light and laser back reflection, 6. Process Head or Scanner, 7. Workpiece

The QD process fiber (3, 5) is connected to a process head or a scanner (6). A fiber-fiber-switch (2) enables the use of up to 4 process fibers that can be monitored in a time sharing mode. The process signals from the fibers are transmitted via power & communication cable (4) to the process monitoring board (1) of the laser device. The laser power and the signals from the active fiber in current use are available at the laser customer interface. The interface supplies real-time signals with a sample rate of 2 kHz which are available as analog (0 – 10 V) or digital CAN bus signals with a high resolution of 16 bit.

3. Cutting

Cutting trials were performed using HighLight FL5000 Fiberlaser with QD process fiber having 100 µm core diameter plugged into Precitecs Procutter cutting head installed in a standard cutting system. Results presented in this paper were produced by high N_2 pressure cutting of 6 mm stainless steel at 4 m/min cutting speed. The cutting process is divided in three different zones (piercing, pre-hole cutting, contour cutting), characterized by different behaviors of the process signals diagramed in Fig. 2 (a).

3.1. Piercing End / Cut Interruption Detection

The programmed piercing process, with a pulse frequency of 150 Hz at a duty cycle of 80 %, lasts 1.05 s and is shown in Fig. 2 (a) as red pulse train. Beginning with the first pulse hitting the workpiece, the visible process emission signal (blue) starts to increase steadily pulse by pulse till the signal drops sharply after 250 ms. This is the moment when the piercing process is successfully finished and the pierce hole is drilled. Using the rapid signal collapse as a trigger, next process step can be started independent from the programmed piercing duration directly after end of piercing is detected.

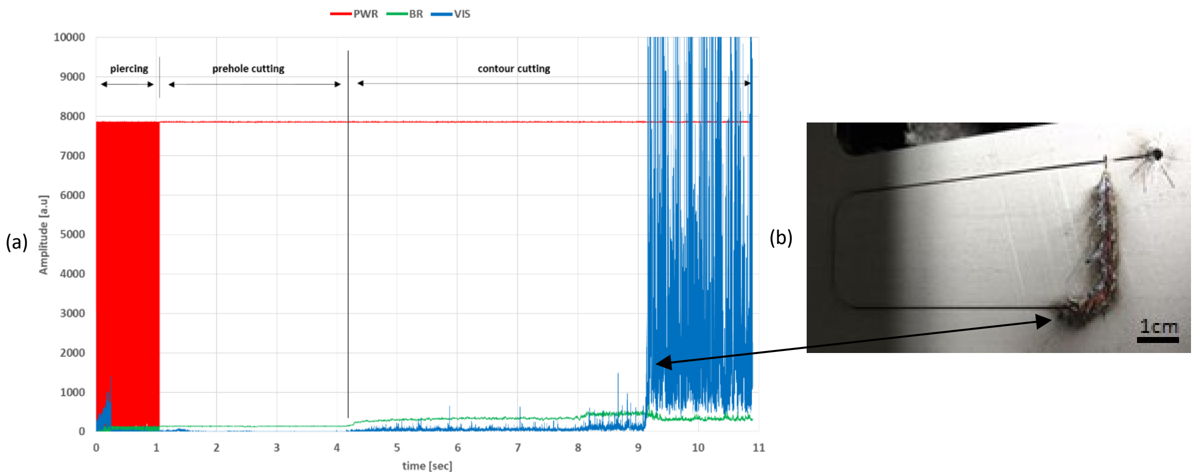


Fig. 2. (a) Raw process monitoring signals of a typical cutting sequence. Red: laser power (PWR), green: back reflection (BR), blue: visible process emission (VIS); (b) Picture of corresponding cutting result

After programmed piercing time finishes, cw laser power is applied to cut an increased hole (pre-hole) at low speed. The pre-hole zone, starting at 1.05 s, is characterized by very low levels of the visible and back reflection signals. The pre-hole itself can be seen on the picture in Fig. 2 on the upper right side and this is the point where the contour cutting starts.

The contour cutting is done with cw laser power and high cutting speed, characterized by increased signals of back reflection and visible process emission, starting at around 4.2 s. Both signals are slightly spiking. The cut interruption in this example is caused by a speed increase above the optimal cutting speed at given laser power. An abrupt rise and a strong fluctuation in the amplitude of the VIS signal starting at about 9 s is related to that cut interruption and marked by the black arrow, pointing to corresponding section in the picture of Fig. 2 (b). The strongly increased signal can be used as a significant information for a machine stop, step back and start cutting again either manually or automatically.

Another interesting information is hidden in the contour cutting signal between 8 and 9 s as this stronger fluctuation and higher amplitude of visible process emission, and slight increase of back reflection signal, points to a different cut quality as in the previous contour cutting sequence from around 4.3 to 8 s. Based on that result a separate measurement was performed to explore the connection between signal amplitude/fluctuation and cut quality in more detail.

3.2. Cut Quality Detection

A high quality cut and two different low quality cuts were generated by adapting cutting speed at given laser power. Lower speed resulted in burr formation whereas a slight speed increase resulted in a so called plasma cut. In Fig. 3 the raw values of the contour cutting sequences are opposed to each other to highlight the difference in signal amplitude and fluctuation by overlaying process signals of the low and the high cut quality. The images contained in Fig. 3 show the low cut quality, which was generated at the short side of the workpiece at the end of the contour cutting sequence.

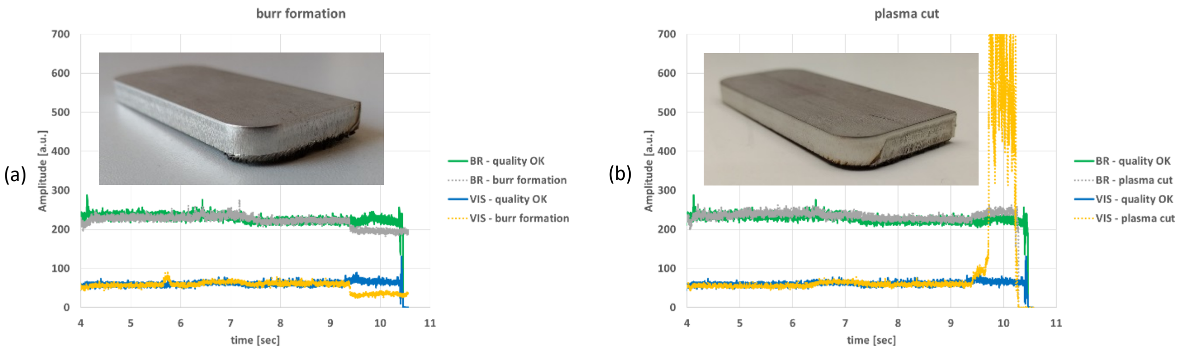


Fig. 3. Process emission signals illustrating contour cutting sequence of (a) high quality cut vs. burr formation cut; (b) high quality cut vs. plasma cut.

Both diagrams in Fig. 3 contain the information about the high quality cut result which is characterized by a very low fluctuating and stable signal level for the two process signals (green – back reflected laser power, blue – visible process emission). Fig. 3 (a) includes the process signals occurring while burr formation (grey – back reflected laser power, yellow – visible process emission) and reveals the benefit of both signals being available as they drop simultaneously at the transition from high quality to lower quality. An opposing trend of process signals is observed during a plasma cut like shown in Fig. 3 (b). The back reflected signal is slightly increased while a significant signal change of the visible process emission is detected. Nevertheless, the amplitude is still considerably lower compared to the strong fluctuating amplitude of a cut interruption shown in Fig. 2 (a).

These results impressively demonstrates the sensitivity and large resolution of the sensors and shows the potential of the laser integrated process monitoring system as a piercing monitor, cut interruption detector and quality monitor for certain cutting applications, whereat low and constant values of both process sensors mirror a high cut quality.

4. Welding

Several weld defects like incomplete penetration due to insufficient power at workpiece, blow holes, gaps or contamination as well as focal shift, material changes and other process instabilities can be crucial for product failure. In-process monitoring systems are able to support the detection of weld defects [Norman, 2007]. In order to evaluate the performance of the laser integrated process monitoring system, standard 1D welding processes and hairpin welding applications were performed to investigate the ability of the system to detect welding defects.

4.1. Failure Detection 1D Welding Process

Welding trials were performed using a HighLight FL5000 Fiberlaser with QD process fiber having 100µm core diameter and optics with a magnification of 1.33 mounted to a robot arm, welding two galvanized mild steel sheets of 0.8 mm. Welding parameters were optimized, resulting in cw laser power of 2.5 kW, welding focus 4 mm below the surface and a welding speed of 4.2 m/min. This results in a welding time for the 187 mm long seam of 2.67 s.

4.1.1. Reference Weld

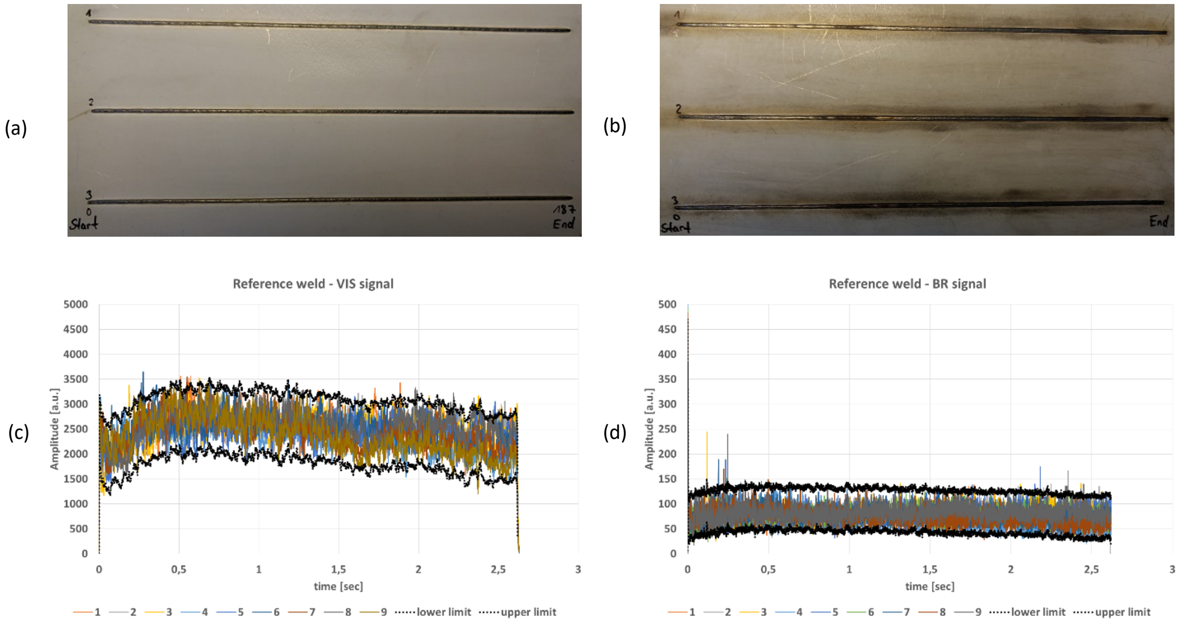


Fig. 4. (a) Upper side of high quality welding result of first three reference welds; (b) Corresponding backside of the reference welds; (c) Raw values of nine high quality welds and generated envelope (black dotted line) of the signals for visible process emission (VIS); (d) Corresponding back reflected laser light signal (BR) including generated envelope

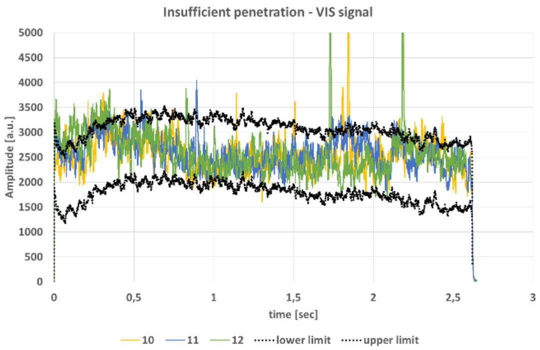
The two process signals of a high quality weld fluctuate and the amplitude changed in a certain range from measurement to measurement. Therefore nine reference welds were performed to generate an envelope of the high quality weld as can be seen in Fig. 4 (a) for visible process emission (VIS) and in Fig. 4 (b) for back reflected laser light (BR). The envelope is diagramed as a black dotted line by an upper and lower limit of the corresponding signal. Single signal spikes outside the envelope, as can be seen for example in Fig. 4 (b), are not part of this analysis as further detailed investigation methods have not been realized at that time. Nevertheless, without deeper analysis of the meaning of single spikes while welding applications, certain failures can be clearly seen on the amplitude and fluctuation of the corresponding signals as shown below.

4.1.2. Insufficient Penetration

Insufficient penetration at workpiece was simulated by adding a third mild steel sheet transverse on the backside of the welding process, shown in Fig. 5 (a). Three similar welds are performed at the same workpiece and overlaid in the corresponding signal in Fig. 5 (b) and (c). A lack of penetration is clearly characterized by a stronger fluctuating amplitude of back reflected laser light out of the envelope whereas the visible process emission signal contains no clear informative value within the raw signal. Single signal spikes outside the envelope, as can be seen in Fig. 5 (b), are not part of this analysis as further detailed investigation methods have not been realized at that time.

(a)

(b)



(c)

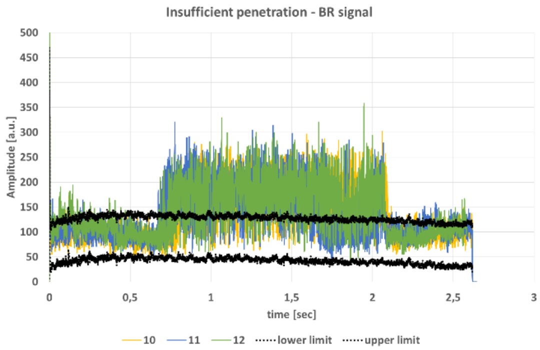


Fig. 5. (a) Picture of the backside of three welds suffering lack of penetration in the middle of the welding process; (b) corresponding VIS signal; c) corresponding BR signal

4.1.3. Contamination

Contamination is a problem which is able to cause spatter, pores or blow holes and is simulated with a 100 µm thin film of industrial fat in-between the two metal sheets. Fig. 6 (a) showing the contaminated zone of roughly 70 mm in the middle section of the metal sheets creating tiny spatters and small blow holes having dimensions < 1 mm at the upper side of the metal sheet while welding, visible in Fig. 6 (b). The corresponding process signals are both characterized by a strong spiking of the signals and are clearly detectable while the laser beam hits the contaminated part of the metal sheets. A different frequency of the spikes of the back reflected laser power compared to insufficient penetration can be noticed. Combined with the visible signal, a differentiation between insufficient penetration and contamination is possible in this case.

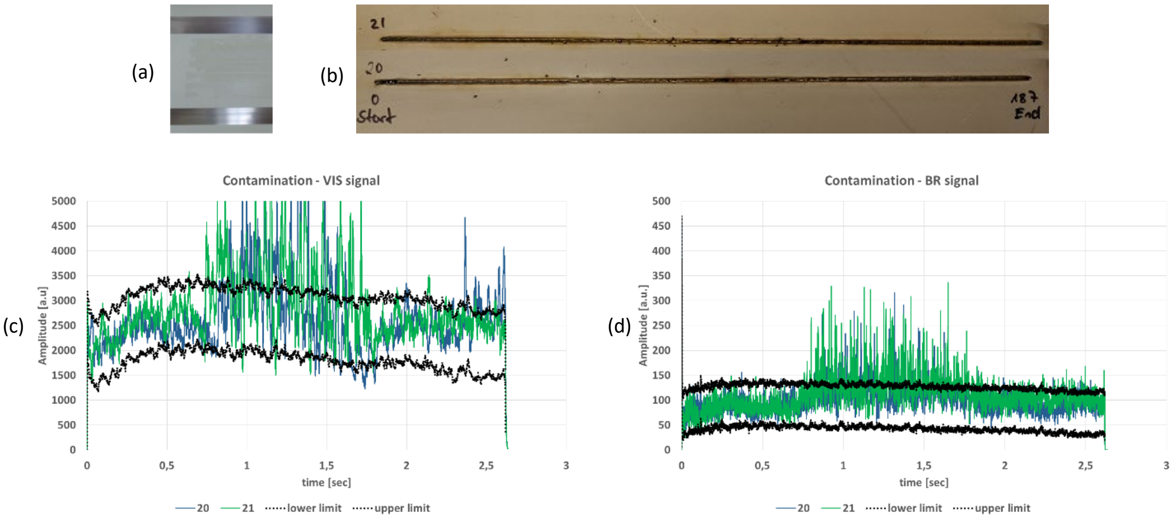


Fig. 6. (a) picture of contamination before welding; (b) picture of upper side of two contaminated welds; (c) corresponding VIS signal; (d) corresponding BR signal

4.1.4. Opening Gap

Gaps can potentially affect the mechanical performance of an overlap joint. To simulate an opening gap, a 0.65 mm thick shim plate is added between the two metal sheets at the right side of Fig. 7 (a). The weld quality degrades with growing gap, which can be identified by a narrowed welding seam resulting in a so called undercut, starting about at the middle of the weld seam till the end. The corresponding process signals are characterized by successive decrease, reduced fluctuation and lower amplitude outside the envelope while an undercut occurs.

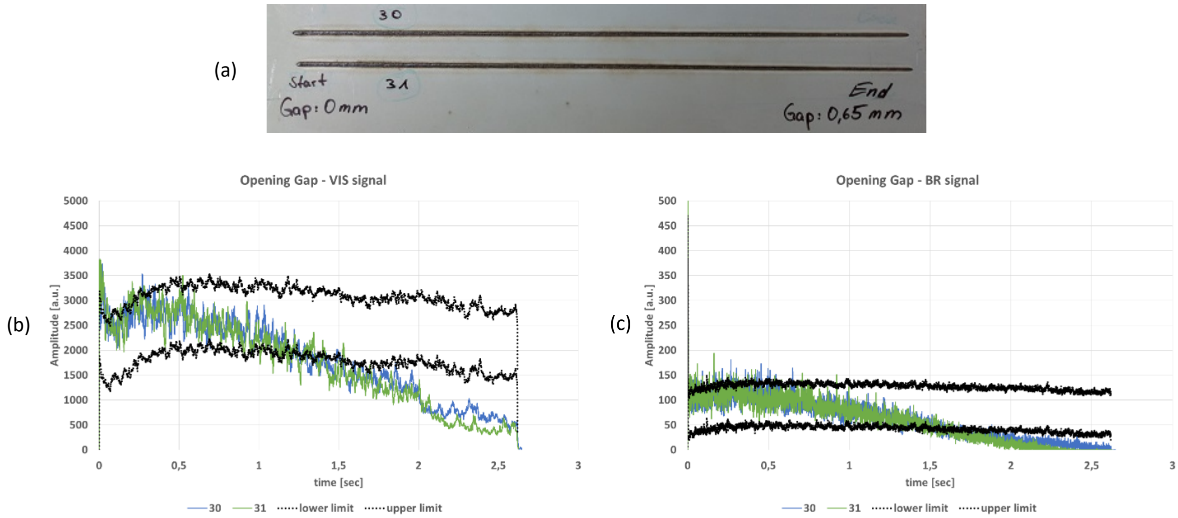


Fig. 7. (a) Picture of upper side of two welds with opening gap increasing from left to right from 0 to 0.65 mm; (b) corresponding VIS signal; c) corresponding BR signal

In this case, an opposing trend of the process signals in contrast to the prior welding defects is clearly detectable. Comparing the welding signals, a differentiation of the shown three weld defects just by two available process signals is possible.

4.2. Hairpin Welding

Stators made by Hairpin technology promises to offer highest potential to fulfill all future flexibility and quality requirements in automotive e-mobility industry with regards to high volume manufacturing. The coil components of the stator consists of a solid electrical conductor with rectangular cross section, so called hairpins. A stator consists of several hairpins and a favorite method to connect open ends of the electrical conductor is laser welding. One option, promising fast manufacturing process times, is scanner welding where the focused laser beam is scanned along the working area, melt the surface and tie two hairpins to each other. Scanner welding offers dynamic control of the temperature in the welding zone by fast movements over the workpiece and is able to heat the material homogeneously leading to a stabilized melt zone with minimal spatter and high conductivity. Correct orientation of the hairpins is one necessary requirement for a high quality weld as misalignments cause a decreased junction area and therefore lower mechanical strength. Investigations of hair pin welding using laser integrated process monitoring showed the value which this system is able to offer as a process control system.

Welding trials were performed using a HighLight FL5000 Fiberlaser with QD process fiber attached to intelliScan30 from Scanlab, integrated into a standard 6-axis welding station.

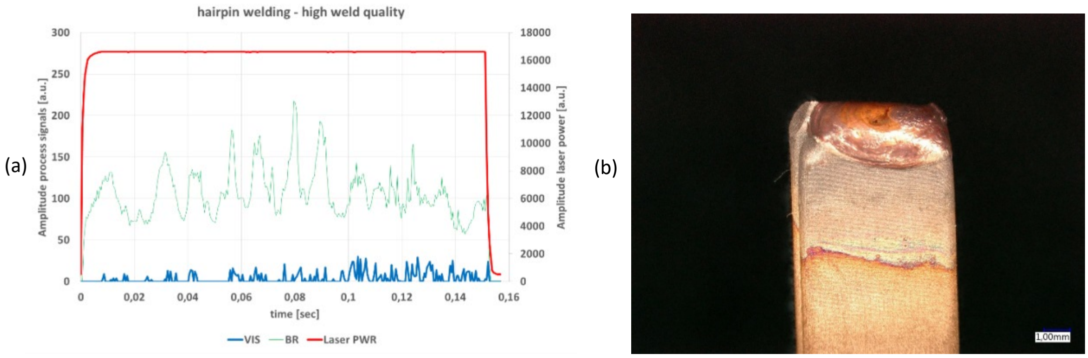


Fig. 8. (a) Raw process monitoring signals of a high quality copper hair pin weld; (b) Corresponding low spatter welding result of high conductivity with homogeneous molten joint

The hairpins used are preprocessed in advance of the weld, by stripping of the isolated coating over a length of about 12 mm at the end of the pins. The weld is realized within 155 ms by multiple elliptical scanning the laser beam along the joint area of the copper elements to melt the material. The process can be observed by the regular modulation of the back reflection signal (BR - green) in Fig. 8 (a). A high quality hairpin weld is characterized by low to zero spatter and a homogenous melting of the material resulting in a low amplitude and low fluctuating visible signal (VIS - blue) as can be seen in Fig. 8 (a) as well. Corresponding high quality weld result is shown in the picture in Fig. 8 (b). Same welding process was realized several times while misalignment of the hairpins. Exemplary the results of height offset of the hairpins is shown.

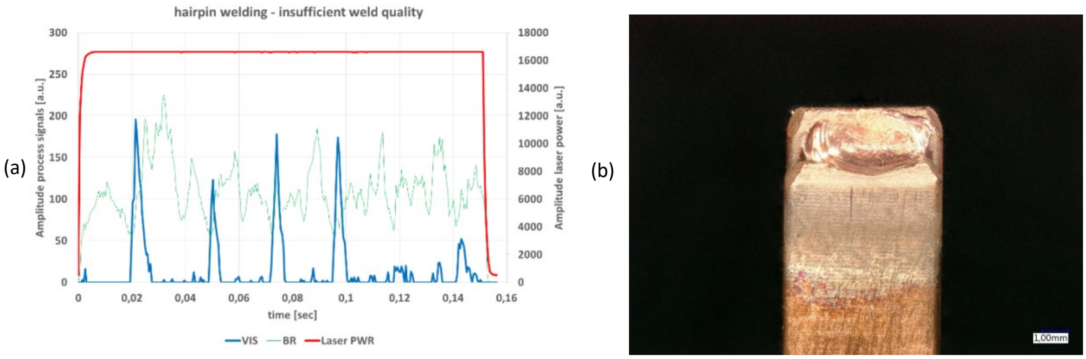


Fig. 9. (a) Raw process monitoring signals of same process sequence when hairpins are not correctly aligned; (b) Corresponding incomplete joint due to misalignment (height offset) of pins

Incomplete joint due to misalignment of pins is characterized by regular peaks of the visible process signal indicating a change of the process to an inacceptable weld quality. The peaks occur when the laser beam hits the isolated area of the hairpin, creating a slight burning of the coating, resulting in a flame detectable by the visible process sensor. The spiking depends on the type and amount of misalignment, whereat gap, v-gap or lateral offset lead to more distinctive peaks than shown in Fig. 9 (a). Variances in the VIS signal, like a general higher amplitude or peaks are indicating a minor weld quality. This can be used for example as significant information for a post-process inspection of questionable hairpins and lead to a direct intervention to the welding process for either manually or automatic correction.

5. Conclusion & Outlook

Laser integrated process monitoring is a powerful tool to verify various process states or failures. In most cutting applications, piercing end and cut interruption are clearly detectable. Besides stainless steel, tests with other materials like aluminum, copper and mild steel revealed similar results. The sensitivity of the system is unfolded by the cut quality tests of stainless steel, resulting in the detection of plasma cut and burr formation. So called self-burning while processing mild steel, is not presented in this paper, but could be detected as well. First tests indicate the usability of the signals to prevent such events by implementing the process signals into a process control system.

For welding processes, the sensors can indicate incomplete penetration due to insufficient power at workpiece, focal shift or material (coating) changes as well as blow holes, contamination, gaps and other process instabilities. Further investigations will be done as different materials and the minimum size of recognizable failures was not part of the welding investigations so far. Implementing a third sensor into the connector, being able to detect infrared light above 1.1 µm, is also under consideration as this would expand the functionality and allow the generation of an improved welding failure detection system.

Hairpin welding is an important part in the manufacturing process of stators for future e-mobility applications. The presented solution is able to deliver significant information which can be added to existing camera based vision systems to increase reliability of the quality control system of the whole welding process.

So far all signals are available as analog (0 – 10 V) or digital CAN bus signals with a sample rate of 2 kHz and a high resolution of 16 bit to be integrated by customer into a process monitoring-, control- or quality system. Soon, for certain cutting applications, status signals will be available at the laser interface, signaling a cut interruption or pierce through. Therefore the laser internal software will be modified to be able to analyze the process monitoring signals. Further expansion to other applications is part of Coherents ongoing investigations of its laser integrated process monitoring solution.

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