

Multi-spectral Monitoring Data in Correlation with X-ray Videography during Laser Welding of Hairpins

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Abstract

In today's production of high-performance electric engines, the hairpin technology is used to increase the efficiency. Instead of a stator made of winded round wire, thicker copper pins are assembled and welded. Typical weld failures such as spatters, pores or insufficient connection occur due to surface contamination, insufficient clamping, positioning or previous cutting processes. For production facilities, it is not sufficient to identify defective welds; a classification is also required in order to determine the causes of the fault and rectify them as soon as possible. The capability of a multi-spectral monitoring system is evaluated in this study with the help of in-situ X-ray videography. The data show a correlation with the stability of the vapour capillary, the welding position and spatter formation.

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1. Introduction

The electrification of the automotive industry is increasing the number of electrically conductive connections per vehicle. To deal with the rising amount of weld seams, laser welding is a suitable process to connect battery cells, power electronics or hairpins. In these applications, a single defective connection can lead to a reduced performance or safety issues. Online process monitoring enables the detection of defects during the laser welding process and helps to increase product quality and long-term stability of electrical connections. By using X-ray imaging during the welding process, it is possible to train the monitoring system also with defects, that are invisible on the weld seam surface after the process. Correlating the X-ray data and monitoring signal will lead to an increased precision of the monitoring system and enable an advanced fault classification. Aiming these goals, in this study, results with in-situ X-ray imaging and multi-spectral monitoring data of the 4D.TWO sensor system are presented.

1.1. Laser welding of copper hairpins

To increase the efficiency, hairpin stators for electric engines are using rectangular copper pins instead of winded round wires. These hairpins are bent, and the insulation is removed in the welding area. After assembling the stator, the neighboring pins are welded to create an electrical connection. Challenges for the welding process are mainly based on welding preparation and clamping (Stäck, 2023):

- Insufficient removal of insulation or contamination
- Lack of reproducibility of the cutting-edge geometry
- Insufficient alignment in height and lateral offset
- Gap between pins due to insufficient clamping

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Besides, welding of copper is usually challenging due to high heat conductivity and low absorption rate for near-infrared lasers. By using lasers with a wavelength of about 1 μm , a keyhole must be created in the copper pins which leads to high energy coupling and weld depth but also to an increased pore and spatter occurrence and higher melt pool dynamic. Resulting pores are reducing the connection area and increase the heat dissipation during operation of the hairpin engine. To reduce the number of pores, Omlor et al. (2023) have successfully used a ring mode laser and oxygen-free copper. D’Arcangelo et al. have benchmarked different types of lasers used for hairpin welding. As a result, near-infrared lasers as well as beam-shaping achieved the best mechanical strength. Nevertheless, a process with so many possible defects and root causes requires a reliable process monitoring to detect faulty weld seams. Process monitoring of hairpins is a key enabler for the efficient production of electric drives.

1.2. Process monitoring of laser welding

Monitoring systems differ in the signal acquisition before, during or after the process. While process defects such as spatters, pores or false friends are mainly visible during the process, these monitoring systems have a high potential. The available systems are using different signals for fault identification, such as surface videography, keyhole depth measurement, acoustic emission, or detection of emitted visible or thermal radiation. (Stavridis et al., 2018) None of these signals can be used as a direct quality measurement but provide valuable information about process stability.

Photodiode sensors that are gathering the radiation emitted by the process are widely used for in-process monitoring in industry (Stavridis et al., 2018). Usable wavelengths are ranging from UV to IR and provide information about the process stability. Welding faults such as spatters or keyhole collapse which might result in pores, are detectable in the process emission. The recorded signals are compared with reference signal levels based on training data. Any deviation from the reference is indicated as a disturbance and might be indicated as a welding fault.

Regarding hairpin welding, 4D Photonics has published results with its legacy product WeldWatcher 6 (Franz and Bruchwald, 2020). In the monitoring signals it was possible to identify gaps between the pins due to different absorption and process emission when the laser beam hits the gap. It was also possible to identify remaining insulation of the copper pins due to insufficient removal. Based on these successful results, the new spectrally resolving sensor 4D.TWO is used in this study to further improve fault detection and analysis of root causes.

2. Experimental Setup

2.1. Multi-spectral monitoring system

The hairpin welding experiments in this study are observed with the newly developed 4D.watcher system with its multi-spectral 4D.TWO sensor. To achieve a precise, reliable monitoring, the process emission light is divided into three main channels with 100 kHz in visible (350-900 nm), laser wavelength range (900-1100 nm) and near-infrared (1100-1700 nm). The visible and near-infrared signals are additionally split into its spectral components to have 16 channels for each wavelength range. This feature enables an application-specific monitoring with the same hardware for multiple different processes. The spectral division of the light allows the recognition of small anomalies in a narrow wavelength range that are not noticeable in a state-of-the-art broadband detection. The channels used for monitoring can be selected according to the application.

Another feature of the sensor system is the lossless technology which allows to monitor high-speed processes with more than 1 m/s. Conventional sensors scan the actual value with the corresponding frequency, whereas the 4D.TWO temporally integrates between two acquisitions. This ensures that no signal peak remains invisible, which allows even very short or fast processes to be monitored reliably.

2.2. Laser welding with X-ray videography

To increase the monitoring capabilities, a correlation between sensor signal and process quality is necessary. After a welding process the weld analysis is mainly limited to a surface observation to see process stability or spatter locations. Identifying pores is even more extensive due to the use of computer tomography or destructive cross-sections. All of these analysis methods are not able to investigate the root cause of the failures. The idea of using in-situ X-ray analysis is to correlate the root causes of the process defect with the sensor signals to qualify the system to monitor the process without the X-ray data afterwards. Therefore, laser welding experiments with Synchrotron radiation – high energy X-ray – and with the 4D Photonics sensor system were carried out at the Deutsche Elektronen-Synchrotron DESY in Hamburg, Germany.

In the setup, the X-rays illuminate the probe from the side. The transmitted radiation is detected on a scintillator screen and recorded with a high-speed camera. Due to diffraction effects at the phase boundaries, the videos show

a grayscale, and it is possible to identify and differentiate the gaseous keyhole, the molten weld pool and solid material. (Hummel et al., 2023)

For the experiments copper hairpins are welded using a Trumpf TruDisk 8001 with a center beam (focal diameter: 166 μm) with 5600 W and a ring with 2400 W. The welding strategy for the presented results was based on three stages: Melting the first pin, melting the second pin and finally join the pins with a circular path affecting both pins.

3. Results and Discussion

For an exemplary analysis, in Fig. 1 selected channels of a hairpin weld are shown. The number of channels is in this case reduced to achieve a better visibility. The illustrated channels show a couple of irregularities. Some of the peaks and dips are numbered and exemplary matched with the x-ray videography in chapter 3.1.

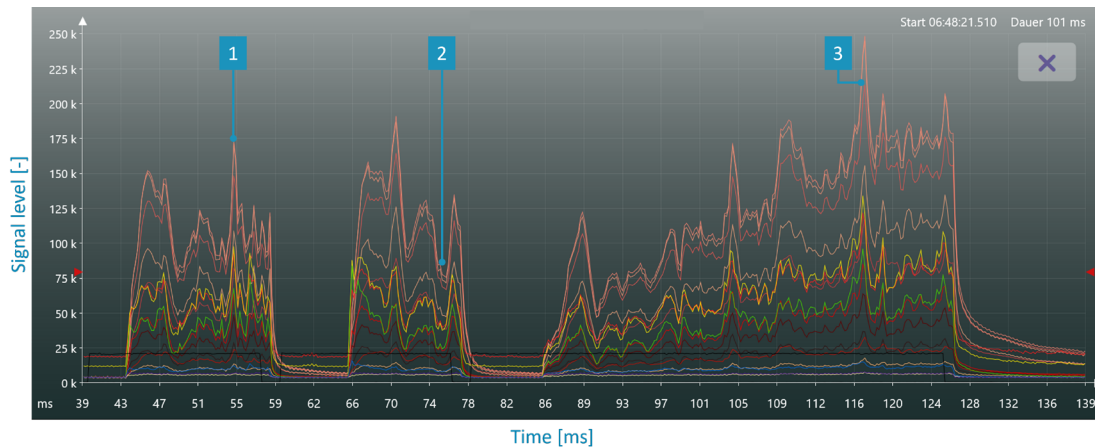


Fig. 1. Multi-spectral monitoring data of a hairpin weld

When looking at the third contour of the processing strategy, a rising signal level becomes obvious. This behavior indicates a higher intensity of the thermal emission in the observed wavelength range and therefore a rising temperature in the welding zone, which is further discussed in chapter 3.2.

3.1. Process Instabilities

Changes in the keyhole stability or geometry usually have a direct impact on the detected signal. An increased keyhole opening due to heat accumulation, shown in Fig. 2 left, leads to a higher amount of radiation escaping the keyhole and entering the sensor (see Fig. 1 label 1). A reduced signal is recorded if, for example, the laser beam is positioned far out on the hairpin. This creates a curved keyhole that is partially open to the side, see Fig. 2 right. Parts of the process emission is in this case not directed towards the optics which leads to a signal dip in the sensor (see Fig. 1 label 2). During hairpin welding this effect may occur due to the cutting edges of the pin.

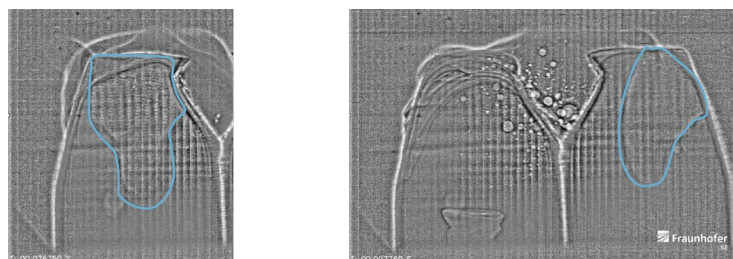


Fig. 2. X-ray images with marked keyhole outline. Left: wide keyhole opening; right: curved keyhole

The special characteristic of hairpin welding is that both pin ends are completely melted at a certain time to form the typical spherical geometry. Temperature gradients in the melt as well as the moving keyhole are creating melt pool dynamics which in turn influences the keyhole. As a result, the keyhole may collapse and spatters or pores can occur. The highest intensity peak in Fig 1 label 3 indicates such a keyhole instability which is visible in the image sequence in Fig. 3. The keyhole depth is changing massively in a period of 5 ms.

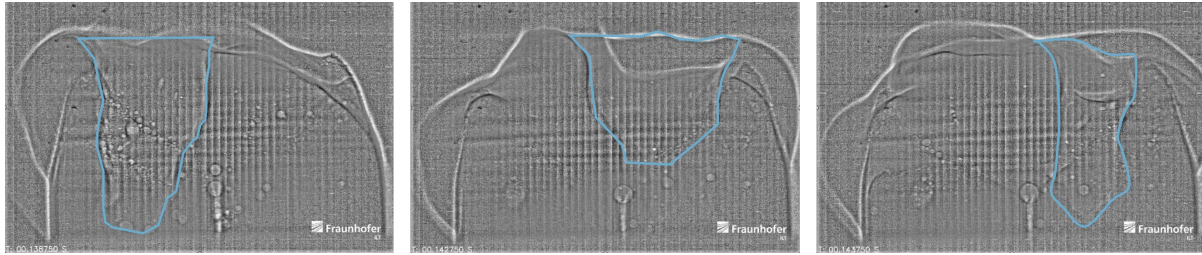


Fig. 3. Keyhole collapse and rebuild in a period of 5 ms

3.2. Ratio pyrometer

By analyzing the near-infrared signal channels, it is possible to create a ratio pyrometer. The ratio between two different near infrared channels is an indicator for the actual surface temperature. A change of this ratio means a change of the temperature. In Fig. 4 the signal ratio is shown for the previously shown weld. Using a smoothing filter leads to a nearly linear rising of the ratio in the third welding contour. A different temperature during the welding might influence the solidification of the melt pool. The cooling curve determines the time for outgassing of bubbles in the melt. A different signal ratio can therefore be a useful indicator for the pore appearance, which is not further investigated in this paper.

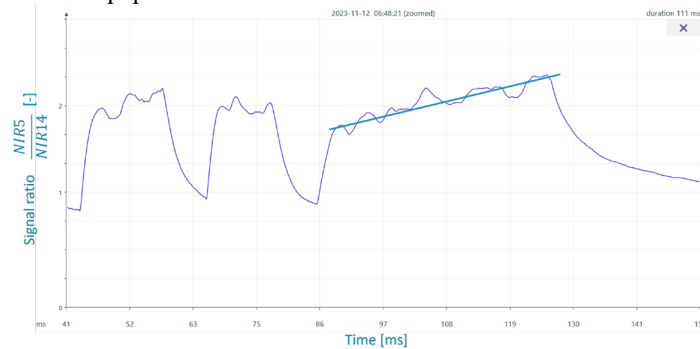


Fig. 4. Combination of channels to achieve a ratio pyrometer

The 4D.watcher system allows the combination of channels with different mathematical operations to create a new monitoring channel. This enables the possibility to specify the channels for each application individually and to highlight certain signal sequences to detect process irregularities.

4. Conclusion

Using X-ray analysis for the welding of hairpins leads to a new insight into the process phenomena that can be correlated with the sensor signal of the 4D.TWO sensor. This additional data supports the understanding of the signal behavior. The presented results show the detection of keyhole instabilities, poor path positioning and temperature changes. The detection of irregularities is the first step to a fault classification which is part of further investigations using artificial intelligence algorithms.

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