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Detecting beam offsets in laser welding of closed-square-butt joints by wavelet analysis of an optical process signal

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HIGHLIGHTS

- Narrow laser welded butt joints are monitored by a photodiode system.
- The photodiode signal is analyzed using continuous wavelet transform.
- The system is evaluated by both continuous wave and pulsed mode laser beam welding.
- The wavelet transform signal detects fast beam deviations from the joint.

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ABSTRACT

Robotized laser beam welding of closed-square-butt joints is sensitive to the positioning of the laser beam with respect to the joint since even a small offset may result in a detrimental lack of sidewall fusion. An evaluation of a system using a photodiode aligned coaxial to the processing laser beam confirms the ability to detect variations of the process conditions, such as when there is an evolution of an offset between the laser beam and the joint. Welding with different robot trajectories and with the processing laser operating in both continuous and pulsed mode provided data for this evaluation. The detection method uses wavelet analysis of the photodetector signal that carries information of the process condition revealed by the plasma plume optical emissions during welding. This experimental data have been evaluated offline. The results show the potential of this detection method that is clearly beneficial for the development of a system for welding joint tracking.

1. Introduction

Robotized laser beam welding (LBW) of closed-square-butt joints enables efficient joining of complex structures giving high quality seams with narrow widths [1]. This is feasible since the laser beam can be focused into a small spot on the work piece. However, due to the narrow fusion zone, the process requires accurate joint preparation, fixturing and robot motion. Besides from this, laser induced distortions may occur during welding and these factors can lead to welding with an offset between the laser beam spot and the actual joint position. Welding with an offset from the joint position may cause lack of side-wall fusion within the seam, as shown in the weld cross section in Fig. 1. This is a critical defect giving a weak seam and it is hard to detect even when using non-destructive test methods. This defect is neither visible on the top nor on the root side of the seam, so non-destructive test methods, such as ultrasonic testing, could fail due to the orientation of the thin defect.

Joint tracking systems are used to avoid this problem and there are several commercial systems available, examples can be found in [2–4]. They use a sensor, usually a camera together with one or several laser lines utilizing the triangulation principle, to measure the joint position and control the laser tool position. However, with machined parts and high fit-up tolerances of the work piece, these systems have low detection probability when the joint gap width and misalignment are close to zero. Scratches may also be present near the joint that can be misinterpreted as the actual joint and mislead the tracking system. In addition, there might be tack welds that covers the joint so that optical detection in that area is impossible.

Several researchers have addressed the issue of joint tracking of zero gap (< 0.1 mm) square-butt joints. The basic concepts for joint tracking

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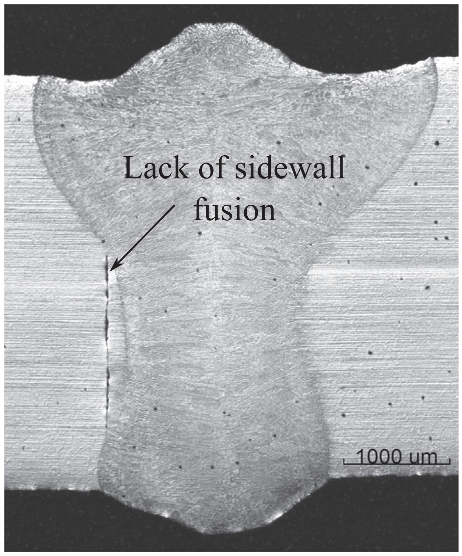

Fig. 1. Cross section of closed-square-butt seam when welded with the laser beam at a 1 mm offset from the joint.

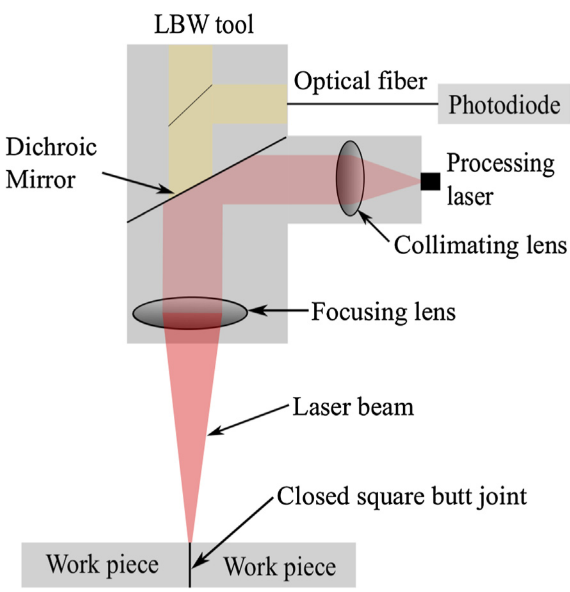

Fig. 2. The LBW tool and its integration of the photodiode.

and specific problems related to this are described in [5], where a multifunctional joint tracking sensor is presented, based on a CMOS camera and low power laser illumination, used for joint tracking and for measuring the displacement between the LBW tool and the work piece. A method to track narrow joints using a CCD camera and a vision algorithm is described in [6], and promising results are shown for an arc welding application. In [7], a texture based algorithm is suggested, where the difference in surface texture of the two work pieces is used to find the joint position from images obtained by a CMOS camera during LBW. In [8], narrow weld joint gaps are tracked using a combination of 2D feature extraction and 3D laser triangulation. An infrared camera, placed in an off-axis configuration, is used in [9] to capture images of the melt pool, and from that information track the joint position during LBW. In [10], a magneto-optical sensor is used to track narrow gaps (< 0.1 mm) during LBW. Although these systems show promising results, this paper investigates the possibility to use a relatively cheap photodiode, which is easy to integrate into an industrial LBW system, for the same purpose.

Many researchers have addressed the issue of finding correlations between the LBW process behavior and the signals from photodiodes. Compared to other optical sensors, photodiodes are inexpensive, fast and easy to integrate into the LBW system. Several commercial monitoring systems are available, using photodiode signals to find correlations to the LBW process behavior, see e.g. [2,11–15]. A feedback control system for full-penetration welding using two photodiodes is presented in [16]. A closed loop system to maintain an even seam is presented in [17], a photodiode is here placed on the root side of the work piece during CO_2 LBW. In [18], a technique is developed for monitoring focus and power variations by chromatic filtering. The relationship between welding defects and a photodiode signal is also investigated in [19], and a mathematical model for numerical simulation is developed. Often, in photodiode-based monitoring and control systems, an upper and a lower threshold are set, and deviations in the LBW process are indicated if the signal is outside these thresholds. The thresholds need calibration for each situation in order not to give false detections and at the same time detect real deviations, which might be a difficult task. It is clear that the signals from the photodiodes hold valuable information about the LBW process, but the interpretation of this information needs to be conducted not just by looking at the level of the raw intensity data from the sensor [12].

More complex signal processing is required to extract the information related to the LBW process quality from the raw photodiode signals. Fuzzy multi-feature pattern recognition algorithms [20] or frequency analyses of the signals through Fast or Short-Time Fourier Transform algorithms have been often used in the past, also for application to LBW process monitoring [21]. However, Fourier methods are not always a good solution to analyze signals that undergo sudden changes, fluctuations or discontinuities, as is the case of LBW. In addition, such methods do not yield a time-resolved analysis of the signals, which is essential to develop in-situ and real-time control systems.

The wavelet transform (WT) provides the frequency analysis of a signal in the time domain, thus enabling a time-frequency representation. There are two different kinds of wavelet transform: continuous and discrete [22,23].

A wavelet is a waveform highly localized in time. In a simple way, Continuous Wavelet Analysis (CWA) can be defined as the convolution of the original signal with a continuously scaled and shifted version of the wavelet function. While the Fourier Transform decomposes a signal into infinite length sines and cosines, effectively losing all time-localization information, the CWA by means of wavelets as basis functions allow for time-frequency analysis. The numerical output of CWA consists of the so-called wavelet coefficients. Wavelet coefficients are evaluated at every possible scale and wavelet functions need not to be orthogonal basis functions.

If only a subset of scales and position is chosen (usually dyadic scales and positions) and if basis functions are required to be orthogonal, then we obtain the so-called Discrete Wavelet Analysis (DWA).

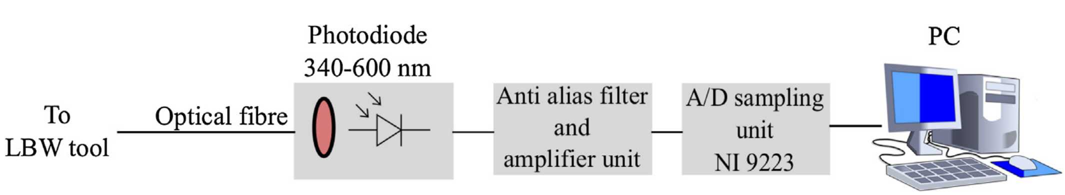

Fig. 3. Principle of the photodiode system.