Lasers in Manufacturing Conference 2015

Online Detection of Pore Formation during Laser Deep-Penetration Welding

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Abstract

Pore formation during laser welding still presents a serious problem. Today, inspection of the weld quality is performed after the welding process. The detection of pores requires non-destructive methods such as computer tomography and ultrasonic testing [1] or destructive methods such as cross-section analysis. The non-destructive methods require expensive equipment and trained staff to perform and analyze the inspection, whereas destructive testing often is not an option when welding only few parts.
In this contribution, a novel online method to detect pore formation is presented. Laser deep penetration welding was observed coaxially using the In-Process Depth Meter (IDM) of Precitec. The IDM is an optical coherence tomography system, which is capable of measuring optical path lengths. The IDM was operated in the IFSW-X-ray system which allows simultaneous time-resolved determination of the depth and shape of the keyhole. It was seen, that in many processes the keyhole is instable. The strong fluctuations in depth and shape often result in the formation of pores [2]. It will be shown, that the keyhole changes its shape in a very specific manner before, while and after a pore is generated. By comparing the X-ray videos and the simultaneously recorded depth data, a signature was found in the measured depth signal, which indicates the generation of a pore.

X-ray; depth measurement; OCT; IDM

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1. Introduction

The occurrence of pores in laser-produced weld seams is often difficult to prevent. This causes the need for sophisticated methods to detect the occurrence of such pores. Critical welds are usually inspected by using either destructive testing methods, such as cross-section polishing the parts and using metallographic etching (Grote, 2007 and (EN ISO 6520-1)). This procedure suffers from two problems: The costs of an additional processing step and the loss of every tested part. To prevent the latter, X-ray or ultrasonic testing is used. Both require expensive equipment and trained staff.

We present a method to detect process pores in the moment when they are formed. By measuring the optical path length of a probe beam, which is aligned coaxially with the processing beam, the depth of a keyhole can be measured [ref!]. In addition, it allows to detect any change of the keyhole shape which causes a change of the optical path length of the measurement beam.

2. Experimental Setup

Simultaneously a side-view was generated using the IFSW X-ray system. A Laserline LDF 4000-8 with a wavelength of 1085 nm was used for the experiments.

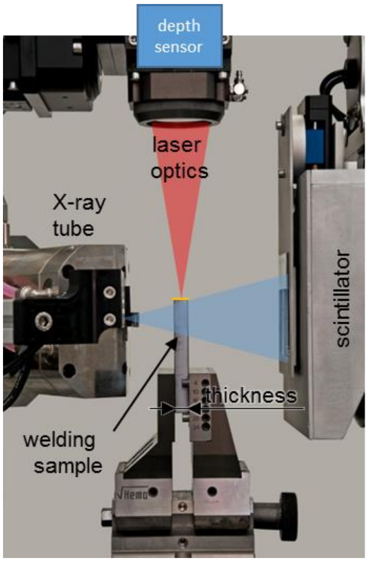
The parameters used for welding were:

- Maximum laser power of 4 kW
- Process fiber diameter 150 µm
- Focal spot diameter 300 µm
- Feed rate 4 m/min
- Inclination angle 10°
- Focal position of 0 mm relative to the sample surface.

2.1. X-ray system

The IFSW X-ray system is shown in Fig. 1. A welding sample with a thickness of 4 mm is used minimize the absorption in the welding sample (Abt, 2010). The processing beam is positioned to target the upper side of the sample, while the X-ray radiates perpendicular to the plane spanned by the laser-axis and the direction of travel, creating a side view of the process as a shadow projection. The sample moves through the laser beam in the direction perpendicular to the image plane. Both, the laser and the X-ray imaging system are fixed in space.

A typical single frame of a time-resolved X-ray record of a deep penetration welding process is shown in Fig. 2. A colored look up table was used to enhance the visibility of different regions. The sample surface is indicated in orange. The keyhole is outlined with a white line for better visibility.



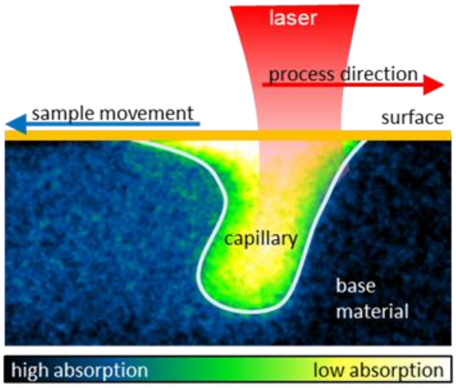


Fig. 1. The sample moves through the laser beam in the direction perpendicular to the image plane. Both, the laser and the X-ray imaging system are fixed in space.

Fig. 2. Typical X-ray image of a deep-penetration welding process.

2.2. Depth measurement system

To measure the depth an In-Process Depth Meter (IDM) from Precitec was used, which is based on the optical coherence tomography. It is capable of resolving an optical path length with 70 kHz and successfully measuring inside the keyhole (Bautze, 2014).

Since it measures optical path length, the depth indicated may not always correspond directly to the keyhole depth. Fig. 3 illustrates different path scenarios for a measurement beam.

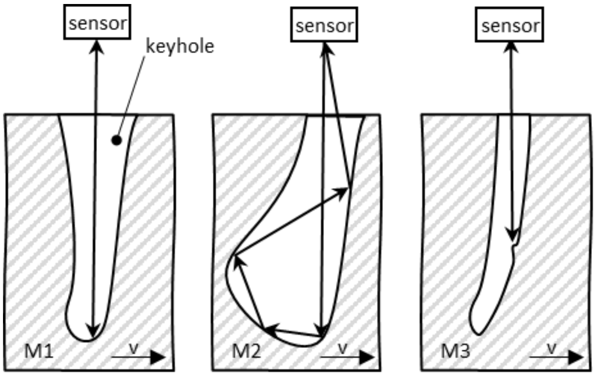


Fig. 3. Different possible measurement cases at typical keyhole geometries.

If the measurement beam hits the deepest point in the keyhole, the measure depth equals the keyhole depth (case M1). In any other case, the measurement does not equal the real keyhole depth. Case M2 will yield a virtually deeper measurement, whereas M3 will result in a smaller measured depth.

Since the measurement beam has a minimum diameter, it is possible to receive back reflections from multiple locations at once. For the experiments only the measured depth with the best signal quality is selected and processed.

3. Formation of pores while laser welding

The formation of a void (i.e. a bubble) in the melt-pool is illustrated in Fig. 4. The keyhole is fully developed, with a straight front in P1. Due to instabilities, the keyhole expands at its tip (P2), starting to create a bubble. The keyhole contracts above the bubble while, according to Katayama, 1998, ambient air or shielding gas is sucked in (P3). When the bubble is fully separated (P4), the keyhole starts to grow again (P5). Not every bubble in the melt-pool will solidify into a pore. We define that have solidified in weld seam as pores and voids present in the liquid melt pool as bubbles.

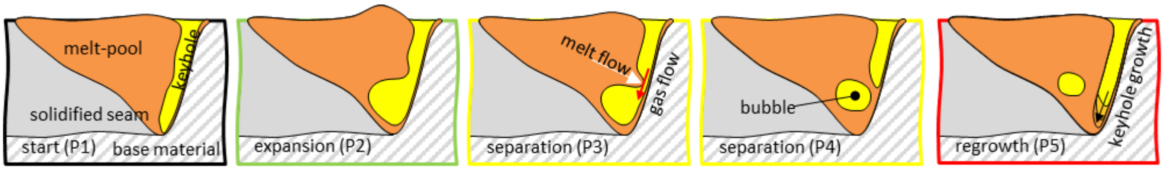


Fig. 4. Simplified sketch of the generation of a bubble in five phases (P1-P5), according to Heider, 2013 and Hohenberger, 2003.

This sequence can be clearly observed by in-situ X-ray imaging of the welding process. Fig. 5 shows an image sequence of the formation of a bubble measured with the X-ray system consistent with the sequence described in Fig. 4.

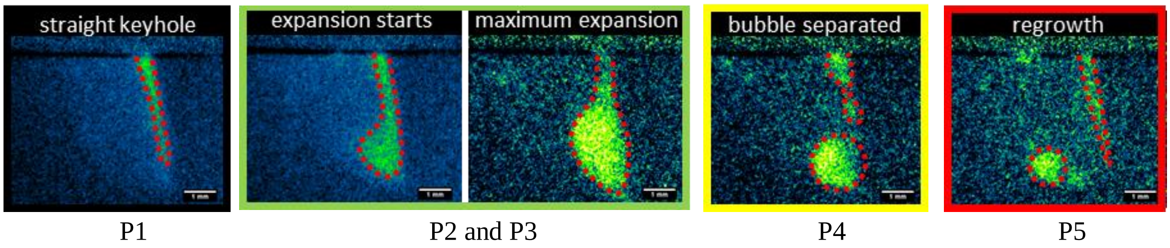


Fig. 5. Bubble generation in AlMg3 recorded with the X-ray system. Time-step between the frames is 1 ms.

4. Indication of pore generation in the depth signal

The above description implies that the keyhole shape significantly changes during the formation of a bubble which could increase the optical path length as described in Fig. 3 (M2). The expected IDM-measurement signal is sketched in Fig. 6. In phase one (P1) a stable keyhole is assumed, which will start to enlarge in phase two (P2). According Fig. 4 the measured depth should decrease in P3 and P4 until the depth is increased again in the regrowth phase P5.

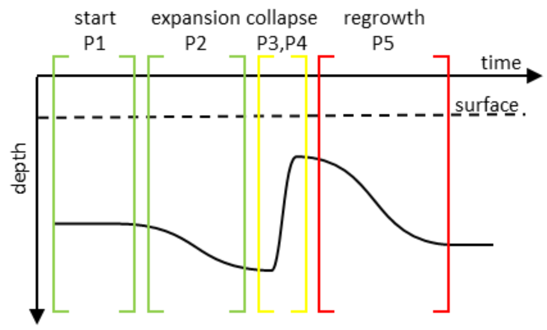


Fig. 6. Sketch of the depth signal during the formation of a bubble. First the tip of the keyhole expands, when the bubble is cut off it collapses and afterwards it regrows.

Fig. 7 shows the formation of a pore (top) and the simultaneously recorded depth signal (bottom). Starting at 140 ms the measured depth increases whereas the keyhole itself increases mainly in width. In between 160 ms and 163 ms the keyhole is cut off and the bubble is separated. From 163 ms onwards the keyhole regrows to nearly the same depth as before.

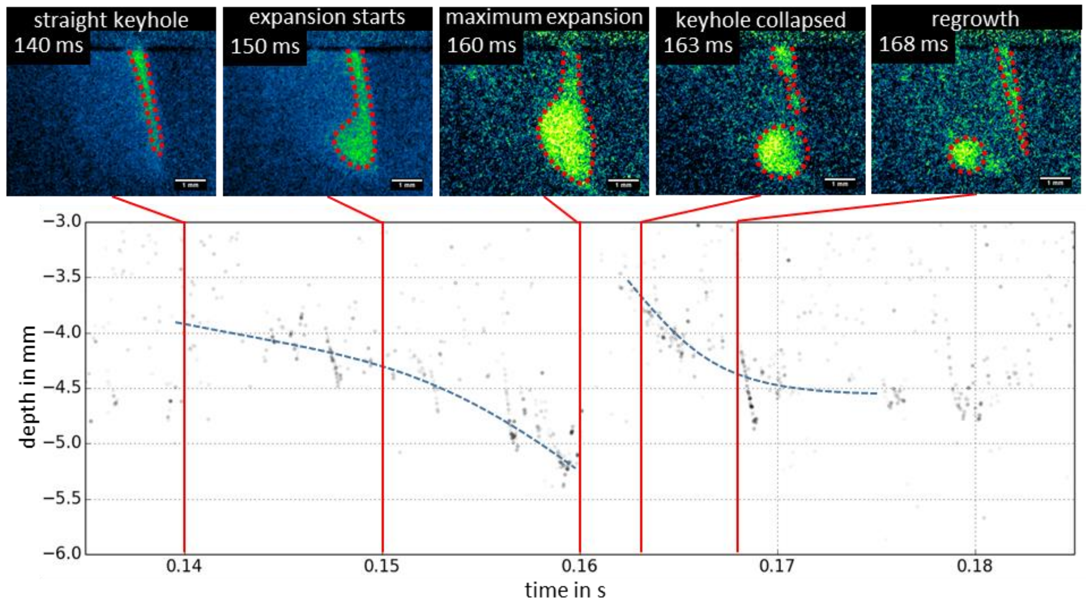


Fig. 7. X-ray video frames illustrating the generation of a bubble along with the corresponding measured depth.

5. Conclusion

It was shown that the formation of a bubble can be clearly correlated to the simultaneously measured depth signal. A distinct signature was seen, which can be used for an automated analysis of the depth signal, e.g. for calculating the number of pores formed in a weld seam.

Acknowledgements

We thank Precitec for supplying us with an In-Depth Process Meter.

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