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The change of the capillary shape during pore formation and its effect on process emissions

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Abstract

Detecting the formation of pores during laser beam welding is challenging as pores are not visible from the outside of the weld seam. However, during formation, pores inherently change the capillary shape, leading to a change in its emissions as well as a change in the back reflection of the laser beam. Monitoring of these emissions has already proven to be a suitable tool in order to determine the formation of defects in welds based on statistical methods and empirical evaluations. To clarify the effect of shape fluctuations of the capillary on its emissions during laser beam welding the capillary shape was recorded by means of synchrotron X-ray imaging and the process emissions were simultaneously measured in different spectroscopic ranges. The analysis of the data proves the connection between capillary fluctuations and characteristic changes of the signals and therefore enables the detection of pore formation.

Keywords: laser welding; pore formation; X-ray imaging; process monitoring

1. Introduction

Laser welding is a highly advantageous joining process in terms of low thermal load and high productivity [Hügel and Graf, 2023]. However, it is important to use an appropriate set of process parameters that will result in weld seams with a low level of defects. Especially for aluminum alloys the range of process parameters to achieve a low level of defects is limited, as shown by Cao et al., 2003. Small changes in the process

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parameters or the workpiece geometry may lead to defects in the weld, such as pores, which are not visible from the outside.

Welding process monitoring has been introduced commercially to avoid the need for costly post-weld seam analysis. An overview of the methods used was listed by Shao and Yan, 2005. One approach to monitor the welding process is the investigation of the process emissions and the back reflection of the laser beam [Eriksson et al., 2009]. Changes in the capillary shape can be detected by the back reflection of the laser beam [Heider et al., 2011; Stritt et al., 2010,]. The narrowing and bulging of the capillary has been described as the dominant reason for a collapse of the capillary, which is associated with pore formation [Matsunawa et al., 2003., Fetzer et al., 2018]. Volatile elements in the alloy or lubricants on the surface of the sample favor the formation of such pores, as shown by Wagner et al., 2021 and Hagenlocher et al., 2020. As stated by Gouffé, 1945 and shown by Fetzer et al., 2018, such a change of the capillary shape changes the total absorptance of the laser beam. A change of the absorptance should therefore have an effect on the back reflection of the laser beam. This article investigates the change in capillary shape during pore formation and its effect on process emissions by analyzing a series of experiments performed with simultaneous X-ray imaging.

2. Experimental setup

The experiments were performed at DESY synchrotron in Hamburg using a synchrotron X-ray beam. The general setup has been already described by Wagner et al., 2021. The samples were made from stainless steel AISI 304 with a thickness of 2 mm, a length of 100 mm and a height of 30 mm. Bead-on-plate welding on the thin edge of the samples was performed so that the propagation length of the X-rays inside the sample is reduced.

A Coherent HighLight FL-ARM fiber laser, which provides a wavelength of 1070 nm, was used for the experiments. This laser combines a single mode fiber laser with a maximum power of 1500 W and a multimode fiber laser with a maximum power of 2500 W, which can be controlled independently. The single mode beam is coupled into the central core of a multicore fiber, while the multimode laser beam is coupled into the ring fiber surrounding the core. The laser beams were focused by processing optics with a focusing lens with a focal length of 400 mm. This results in a center spot diameter of 67 µm and a ring spot diameter of 450 µm at the focus position on the sample surface. The samples were moved relative to the static processing optics and the X-ray beam. The X-ray images of the welding process were captured by recording the emitted light of a scintillator with an i-Speed 727 highspeed camera at a frame rate of 10 kHz.

The Laser Welding Monitor LWM 4.0 system from Precitec was used to measure the emissions from the welding process. The sensor measures the back-reflected laser beam as well as emissions in the visible and near-infrared range at a frequency of 50 kHz. The sensor was mounted coaxially to the processing optics and aligned to the laser spot.

3. Results

In order to investigate the changes in capillary shape during pore formation and its effect on process emissions, welds were made at different laser powers in the center and ring fiber spots at a welding speed of 12 m/min. Welding with a laser power of 400 W in the center spot and no power in the ring spot produces a narrow and deep capillary. However, the stability of the welding process is poor, so that the capillary depth decreases sporadically. This behavior can be seen in the series of images in Fig. 1. At 101.2 ms after the start of the welding process, a deep and narrow capillary is visible. Only 0.8 ms later, at 102.0 ms, the depth of the capillary is significantly reduced. Another 0.8 ms later, the capillary is deep again.

The corresponding measured signal of the laser back reflection is also shown in Fig. 1. The signal values are well below 1 V for the deep and narrow capillary. As the capillary shape changes, the laser back reflection increases strongly. As the capillary depth increases again, the signal values decrease to the lower level again.

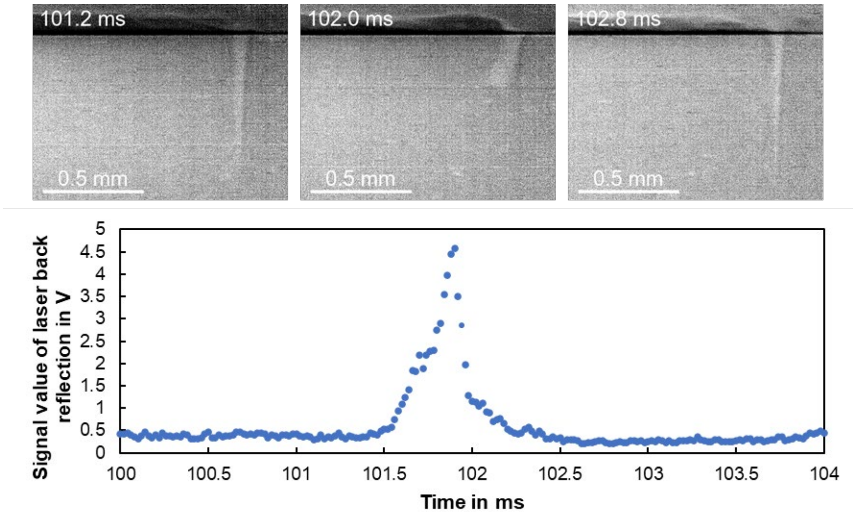

Fig. 1: Signal value of the laser back reflection over the time of the welding process with corresponding X-ray images of the capillary.

This observed behavior is in good agreement with expectations from the literature. The formation of a deep and narrow capillary leads to a high absorptance of the laser power and therefore to a reduced back reflection. This result demonstrates, that changes in the capillary shape affect the back reflection of the laser beam.

The effect of changes in the capillary shape during pore formation and its influence on the laser back reflection was observed in experiments with a laser power of 300 W in the center spot and 1200 W in the ring spot. These process parameters lead to the formation of many small pores detaching from the tip of the capillary. To investigate the porosity, the X-ray images from the already solidified part of the sample have been superimposed in order to get an image of the whole sample. A 15 mm long section of this image from the middle part of the weld can be seen in Fig. 2 a) with an enlarged view of the pores in Fig. 2 b). Image processing methods were used to mark the pores in a binary image with the pores marked in black and the surrounding solid metal in white, as can be seen in Fig. 2 c).

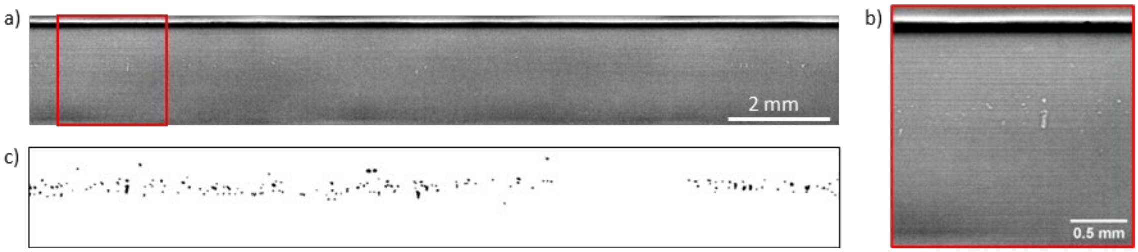

Fig. 2: a) X-ray scan of a sample welded with 300 W in the center spot and 1200 W in the ring spot, b) enlarged view of a part with pores, c) binary image with marked pores

To quantify the porosity, the pixel values of the binary image from Fig. 2 c) were added line by line. This step allows the approximation of the porosity along the weld seam. The result is shown in Fig. 3 as normalized pore area over the position of the weld seam. It is clearly visible that the predominant part of the weld seam contains pores. However, in the region between 20 mm and 22 mm after the start of the welding process no pores are visible in the weld seam.

The corresponding signal of the laser back reflection is also shown in Fig. 3. The excerpt of the signal of 75 ms duration corresponds to the 15 mm long section of the weld at a welding speed of 12 m/min. The signal values of the laser back reflection are between 1 V and 4 V most of the time and are therefore higher than in case of the deep and narrow capillary shown in Fig. 1. In the period of time between 100 ms and 110 ms after the start of the welding process the signal values of the laser back reflection are significantly increased.

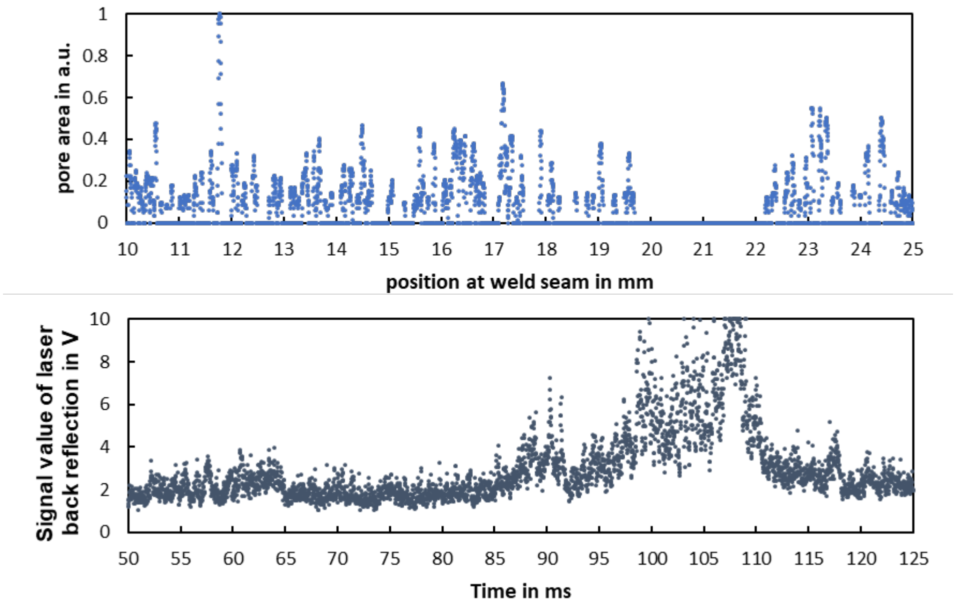

Fig. 3: Pore area over the length of the sample and signal value of the laser back reflection for the welding process with 300 W in center spot and 1200 W in ring spot.

Analysis of the X-ray images shows that for the period of time when the signal values of the laser back reflection peak, a change in the capillary shape can be seen compared to the normal shape at these process parameters. With the change in capillary shape no pores are forming during this time period. Linking these measurements shows that the change in capillary shape results in a reduction in the porosity of the weld and that this change can be seen in the signal of the laser back reflection.

4. Summary

The change in capillary shape during pore formation and its effect on process emissions was studied using simultaneous high-speed synchrotron X-ray imaging. The results show a strong correlation between changes in capillary shape and the measured signal of the back-reflected laser beam. Furthermore, in an unstable welding process, it was shown that pore formation due to a change in capillary shape can be detected in the signal of the back reflection. However, for a more time-resolved view, further analysis is required.

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