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SciVerse ScienceDirect
Physics Procedia 41 (2013) 539 – 543
Physics Procedia

Lasers in Manufacturing Conference 2013

Detection of weld defects by high speed imaging of the vapor plume

C. Brock[a,b,*], F. Tenner[a,b], F. Klämpfl[a], R. Hohenstein[a,b], M. Schmidt[a,b]

[a]Institute of Photonic Technologies, University of Erlangen-Nuremberg, 91052 Erlangen, Germany
[b]Graduate School in Advanced Optical Technologies, University of Erlangen-Nuremberg, 91052 Erlangen, Germany

Abstract

Using two high speed cameras, we analyzed the 3D vapor plume fluctuations during laser welding of steel sheets in overlap configuration. Our results indicate that the position of the vapor plume contains relevant information on the process state. Whereas an increase of the penetration depth shifts the plume position in negative welding direction, welding defects like spatter formation or holes in the weld seam cause strong fluctuations of the plume position laterally transverse to the welding direction.

Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)

Keywords: laser welding; process monitoring; high speed imaging

1. Introduction

In laser deep penetration welding, the workpiece is irradiated with focused laser light of high intensity (>10^6 Wcm^{-2}). Consequently, the material melts and partially evaporates, leading to the formation of a vapor capillary or "keyhole" [Dowden 2009]. As the stability of the welding process is directly related to the stability of the keyhole [Pan 2011], various efforts have been made to understand the formation and evolution of the keyhole during the welding process. Direct observation methods using e.g. high speed cameras may provide important information on the process dynamics, but are limited to the top region of the capillary

* Corresponding author. Tel.: +49 9131 85 23256
E-mail address: christian.brock@lpt.uni-erlangen.de

Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)
doi:10.1016/j.phpro.2013.03.113

[Schmidt 2008, Erikson 2010] or the detection of special characteristics like the full penetration feature [Weberpals 2008]. Indirect observation methods based on the detection of optical, thermal or acoustic process emissions suffer from ambiguous correlation of the detected signal intensities with the welding state [Norman 2008].

Therefore, current research focuses on the identification of measurable process properties that show non-ambiguous correlation to the actual welding state. Dorsch et al. have shown that the geometry of the melt pool may fulfill this criterion [Dorsch 2012], whereas Fabbro et al. studied the inclination of the vapor plume and found a relation between the plume inclination and the orientation of the front keyhole surface when welding thin steel sheets [Fabbro 2010]. Using a coaxially installed camera, Blug et al. implemented a closed loop control of the laser power in order to maintain the full penetration state. To this end, they detect a feature in the camera images caused by the opening of the keyhole at the bottom of the workpiece ("full penetration hole") [Blug 2011].

In the study presented in this paper, we provoked different process states by changing the laser power or feed rate when welding steel sheets in overlap configuration and analyzed the three-dimensional shape of the vapor plume corresponding to the respective weld.

2. Experimental

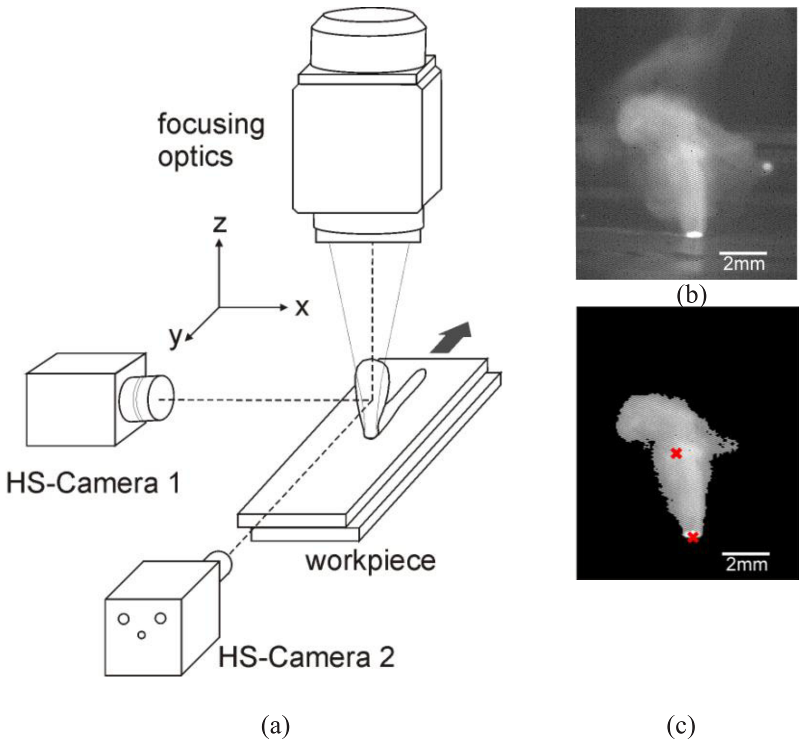

Fig. 1. (a) Experimental setup. The incident laser beam, the observation direction of camera 1 and the observation direction of camera 2 include 90° angles each. (b) Exemplary image recorded by camera 1. (c) Processed image. The red crosses indicate the calculated keyhole position and the center of the vapor plume.

A TruDisk 4002 Yb:YAG laser (wavelength 1030 nm, maximum output power 4 kW) coupled to focusing optics (BEO D70, focal length 200 mm, spot size 0.6 mm) was used to weld steel sheets (S235) in overlap configuration. While the focusing optics remained at a fixed location, the workpiece was moved by a robot (Kuka KR125) at the desired feed rate. Two high speed cameras were installed to synchronously image the vapor plume during the welding process as shown in Fig. 1a, with a frame rate of 6000 fps and an exposure time of 2µs. Reflected laser light was blocked by an optical shortpass filter.

In each image of a high speed sequence the background was removed by dynamically thresholding the gray scale values. Using morphological operators such as dilation and erosion the image was segmented into plume and non-plume zones, then the keyhole position, the plume center and the plume size were determined. It is important to note that by determining the position of the keyhole in each image and calculating the plume center with respect to that position, we prevent errors that otherwise would be introduced by robot vibrations or heat induced surface expansion.

3. Results and Discussion

In our first experiment steel sheets of 1 mm thickness were joined at a constant feed rate of v=7 m/min in overlap configuration while the laser power was increased stepwise from 1 kW to 3.5 kW, resulting in a stepwise increase of the penetration depth (full penetration not reached, see Fig. 2b). The image analysis shows (Fig. 2a) that the mean x-component of the vapor plume center remains constant during the weld, whereas the mean y- and z-component decrease as the laser power is increased.

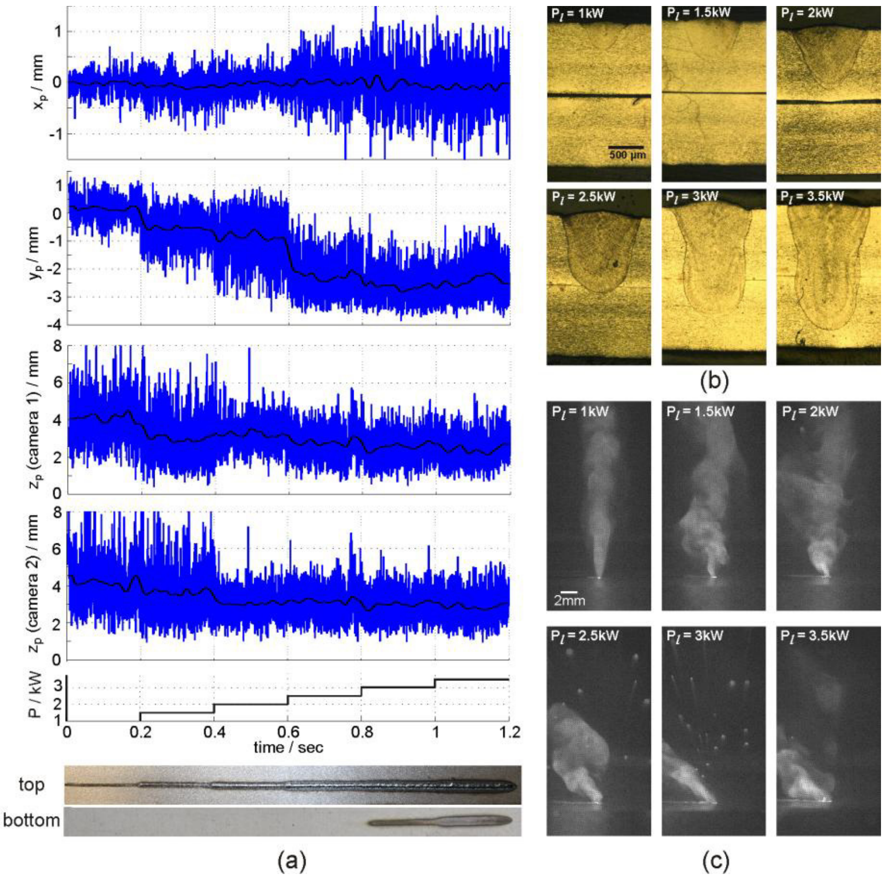

Fig. 2. (a) Trajectory of the vapor plume center relative to the keyhole position (blue) and low pass filtered curve (60 Hz, black). A stepwise increase of the laser power causes the plume to tilt towards the meltpool. The slight differences between the z-component z_p detected by camera 1 and camera 2 result from the segmentation algorithm, due to the different perspectives of the cameras. (b) Transverse microsections of the weld seam for each step of the laser power ramp. (c) Exemplary images of the vapor plume recorded by camera 1 for each step of the laser power ramp.

This means that the vapor plume inclines in direction of the melt pool as the penetration depth increases. For laser power settings up to 2.5 kW a weld seam of good quality was obtained. For laser power settings of 2.5 kW and higher, we observed strong spatter formation. This instability causes the plume to fluctuate strongly laterally transverse to the welding direction, as can be seen by the increasing fluctuation of the x-component at t=0.6 s. This experiment was repeated twice, yielding similar results with variations of the mean values smaller than 2 %.

The z_p-component of the plume measured by camera 1 and camera 2 shows slight differences. When processing the images bright sections with an area smaller than 500 pixels (corresponding to an area of 1.02 mm^2) were filtered off. In this way spatter or small side vapor jets are not taken into account when the plume center position is calculated. Since camera 1 and camera 2 have different angles of view, a small region may be filtered off by one camera while being taken into account by the other, resulting in the slightly different evolution of the measured z_p-components.

In a second experiment two steel sheets of 0.5 mm thickness were joined in overlap configuration with a constant laser power of P=4 kW. The first part of the resulting weld seam is of good quality and the vapor plume position is quite stable. After t=0.9 s the feed rate was increased from 4 m/min to 7 m/min, inducing

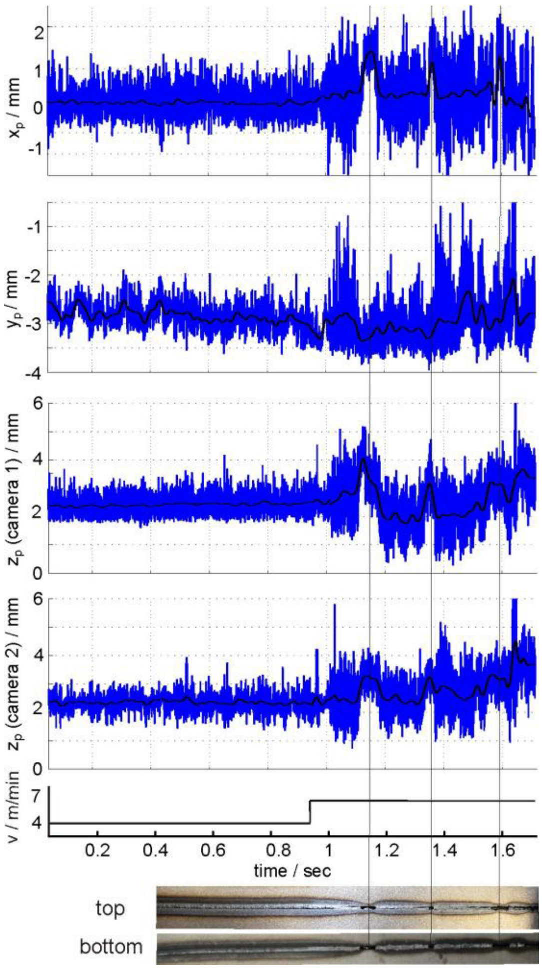

Fig. 3. Trajectory of the vapor plume center relative to the keyhole position (blue) and low pass filtered curve (60 Hz, black). An increase of the feed rate from 4 m/min to 7 m/min results in an unstable process. The occurring instabilities strongly affect the x_p- and z_p-component of the vapor plume center whereas the y_p-component is not directly changed. The length of the weld seam shown at the bottom does not match the time axis in the first part of the weld since the feed rate was changed at t=0.9 s.

process instabilities that lead to the formation of holes in the weld seam. For both feed rates the laser power of P_l=4kW is sufficient to keep the welding state in full penetration. Increasing the feed rate increases the velocity of the melt flow around the keyhole, creating a situation comparable to remote fusion cutting [Schober 2012]. Yet, at the chosen parameters the process does not reach a stable state, but changes between welding and cutting in an unpredictable way. The holes in the weld seam that result from these instabilities cause strong variations of the x- and z-component of the vapor plume, while the y-component becomes less stable but is not directly affected (Fig. 3).

4. Conclusion

The current experimental results indicate that the position of the vapor plume does not behave chaotically, but responds to changes in the welding state in a reproducible manner. We were able to indentify a correlation of the y- and z-component of the vapor plume center position with the penetration depth of the weld. We also observed that the stability of the vapor plume position responds to the occurrence of welding defects such as spatter formation or the formation of holes in the weld seam.

These findings indicate that information on the process state (i.e. keyhole geometry) can be obtained by the evaluation of the shape of the vapor plume during the welding process. The identified correlations may allow for the implementation of a closed-loop control system based on the detection of the vapor plume position.

Acknowledgements

The authors gratefully acknowledge the support received from the Erlangen Graduate School in Advanced Optical Technologies.

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