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Camera based closed-loop control of laser micro-welding processes by observation of the full penetration hole

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Abstract

In macro welding-processes, monitoring and closed-loop control by using the so-called "full penetration hole" is well known. This paper reports first results for the transfer of this technology to laser micro-welding processes for lap joints as they are used for housings or fuel cells. The laser source was a 400 W cw fiber laser with a Gaussian beam profile and a spot size of 28 µm. A cellular neural network (CNN) camera was used to measure the image feature of the full penetration hole within the thermal image of the welding process. For full penetration weldings on stainless steel samples, the laser power was controlled by the rate of full penetration hole detection. The effect of the feedback system is that the laser power is automatically adapted to changes in sheet thickness or feeding rate. The sheet thickness was varied between 220 and 350 µm and the feeding rate between 10 and 40 m/min without significant change in the weld seam quality. The closed-loop system increases the robustness of the process against perturbations and the process is always guided at the minimum laser power necessary for full penetration thus reducing spatter and smoke residues.

Keywords: Micro-Joining; Process Monitoring and Control

1. Introduction

Electro mobility is a driving application for the development cw lasers micro welding processes for enlarged housings of batteries or fuel cells with high capacities. Therefore, the transfer of a closed-loop system from macro to micro cw laser beam welding processes was investigated. It is based on a camera evaluating an image feature called "full penetration hole" (FPH). This image feature appears as a dark spot

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within the thermal radiation from the keyhole of the laser welding process when the melt pool reaches certain interfaces like the bottom of the work piece or the gap. Bardin et. al. published one of the first successful closed-loop systems exploiting FPH [1]. They evaluated the contrast of the keyhole with conventional silicon cameras without resolving the fluctuations of the melt. In the full penetration weldings they were able to compensate sheet thickness and focus drifts by adapting the laser power. Alternatively, the statistics of the FPH can be evaluated [2]. When the welding depth is close to the bottom of the work piece or close to the gap in overlap joints, the rate of FPH detections rises. In these two regimes the closed loop system keeps rate of FPH detections constant by adapting the laser power. In this way the system is able to control the penetration depth relative to the bottom of the work piece (“full penetration”) or relative to the gap in lap welds (“partial penetration”, [3]) in macro welding processes.

2. Experimental setup

For the welding experiments a 400 W fiber laser with wavelength of 1070 nm and a Gaussian beam ($M^2 < 1.1$) was used. The beam radius at the fiber exit is 2 mm. The laser is integrated into a laser machine with flying optics, i.e. the work piece is fixed and the focusing optics with a focal length of 50 mm is moved in x, y, and z direction. The NIR radiation from the process is directed to the camera through a dichroic mirror (Fig. 1a). It is magnified by a double lens telescope and restricted to a spectral range of 870 to 930 nm by an optical filter. The spot size of the Gaussian beam on the work piece was estimated to 28 µm. All welds presented here were overlap joints with a length of 35 mm in stainless steel material. (Fig. 1b).

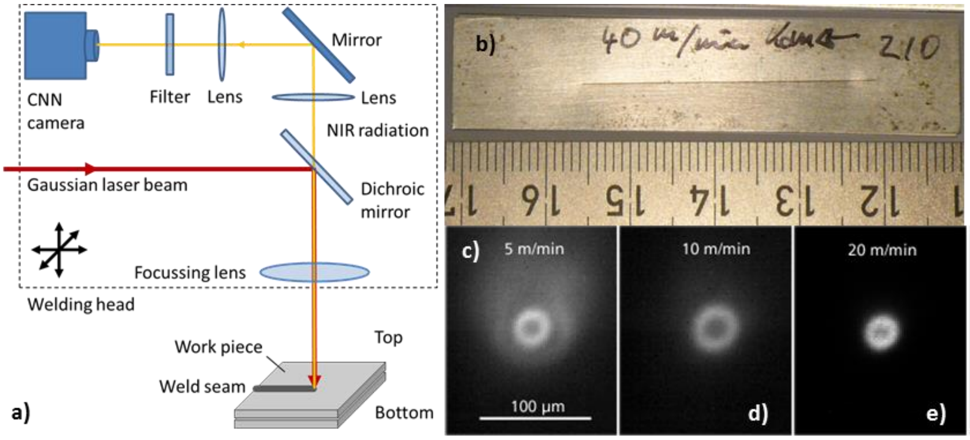

Fig. 1: Sketch of the optical setup of the welding head (a), weld seam with a length of 35 mm (b) and typical images of full penetration holes at 5 m/min (c), 10 m/min (d) and 20 m/min (e). The bright spots in (c, d, e) have the diameter of the laser spot (30 µm).

The key component of the setup is the camera based on cellular neural networks (CNN). The CNN can be regarded as a technology to integrate a processor into every single pixel of the camera. The result is a sensor-processor network where image processing takes place directly on the sensor chip [4]. Due to this technology the FPH can be detected with frame rates up to 14 kHz and the delay time for the feedback of the laser power P is in the range of 100 µs. The major difference to the closed-loop setup for macro welds described in [2] is the magnification of the camera optics. The image resolution on the work piece is 2.2 µm/pixel rather than 16 µm/pixel in order to resolve the laser spot of 28 µm. The enlarged magnification reduces light intensity. Therefore the frame rate of the camera was limited by the exposure time to 3 kHz. For the detection of the FPH as shown in Fig. 1 the omnidirectional algorithm was used [5].

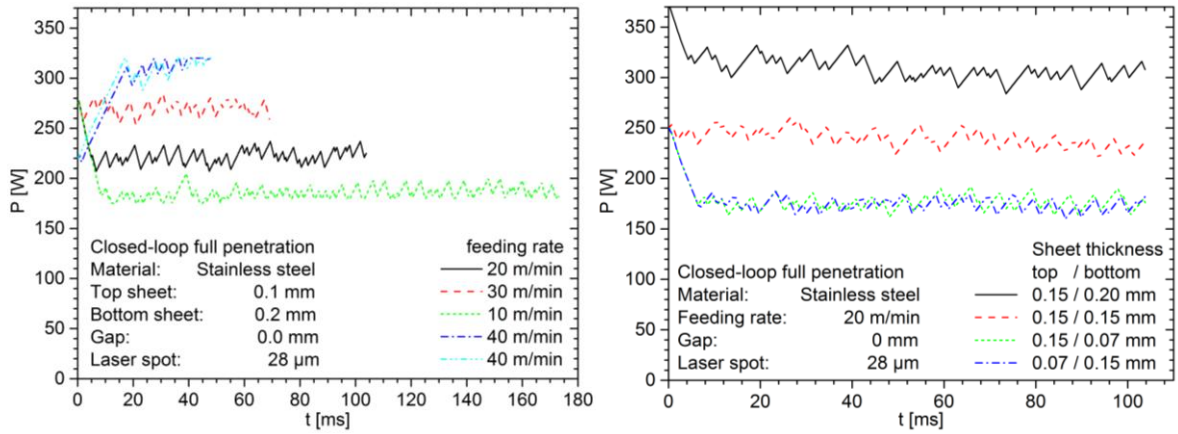

Fig. 2: Response of the closed-loop system to variable feeding rates (left) and sheet thickness (right).

3. Closed-loop results

The set point of the closed-loop system is a constant FPH detection rate of 33.3 %, i.e. one FPH event in three images. The laser power is reduced when more FPH events are detected and increased at lower detection rates (details in [6]). Fig. 2 shows two examples for the response of the system: At higher welding speeds the penetration depth decreases. Therefore, less FPH events are detected and penetration depth is increased by laser power. Similarly, laser power is adapted to sheet thickness because the process is always guided at the minimum laser power necessary for full penetration. Fig. 3 shows some resulting weld seams. Although welding speed is varied by a factor of four, the weld seams have a constant width which varies only between 50 and 80 µm. As the width of the heat affected zone (HAZ) indicates, this variation is due the process efficiency which increases with welding speed. Similar results were obtained when the total thickness of top and bottom sheet was varied between 240 and 350 µm. The limit was the focal depth of the CNN camera optics in the welding head (± 60 µm).

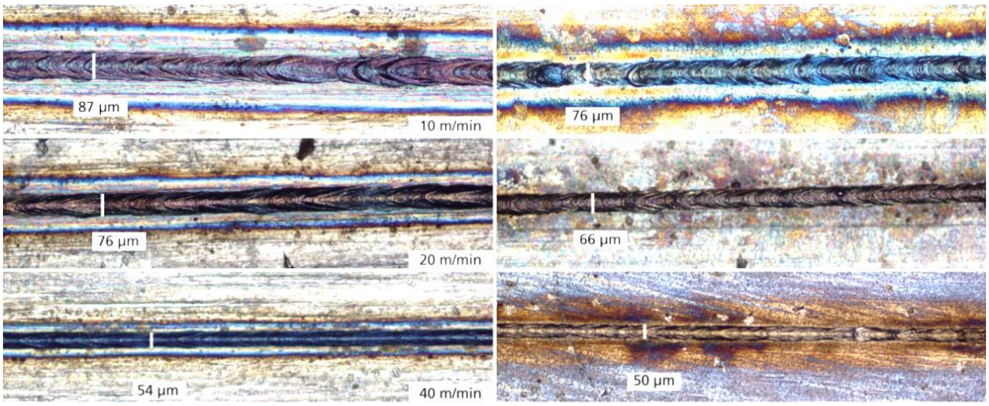

Fig. 3: Microscope images of top (left) and bottom (right) weld beads of closed-loop processes at different feeding rates.

Fig. 4 shows weld seams obtained without closed-loop control for comparison. The laser power was fixed at 220 W, i.e. the average value at 20 m/min. At that speed, the welding results are the same. At 10 m/min, line energy is doubled. As expected, smoke residues increase and the whole weld seam exhibits a variable width on top and bottom bead. At 30 m/min, the bottom weld seam becomes irregular, too, and full penetration is lost in some areas. At higher feeding rates, no bottom weld bead is visible anymore. This demonstrates that the robustness is increased significantly by the closed-loop system.

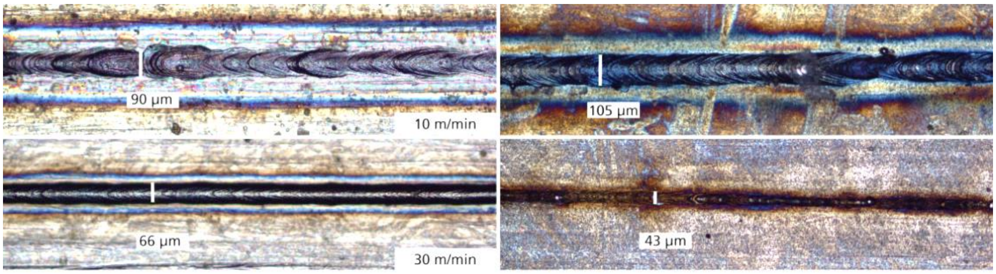

Fig. 4: Microscope images of top (left) and bottom weld beads (right) of reference processes without closed-loop. The laser power was 220 W. At 30 m/min the bottom weld bead becomes irregular and it vanishes completely at 40 m/min.

4. Conclusion

These results show that the concept of controlling penetration depth by adapting laser power to a frequency of full penetration holes – as it is described for macro processes in [2] - is transferable to full penetration micro welding processes using a laser in cw mode. The major difference is the higher magnification of the camera optics. The field of view is defined by the spot size of the laser (28 µm). To resolve the FPH within this spot the image resolution was chosen to 2.2 µm on the work piece surface. The result of the closed-loop control is that process drifts are compensated – as it has been demonstrated for feeding rate and sheet thickness.

Closed-loop control of partial penetration processes is not possible yet with this configuration because no FPH events were observed at the gap between the sheets. So far, the reason is not clear. It might be caused by the different material (stainless steel instead of zinc coated steel) or by the geometry of the weld pool, because the laser beam had a Gaussian instead of a top head profile which alters the geometry of the melt pool. Here, further investigations are required.

Acknowledgements

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