Camera Based Closed Loop Control for Partial Penetration Welding of Overlap Joints


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Abstract

Welding of overlap joints with partial penetration in automotive applications is a challenging process, since the laser power must be set very precisely to achieve a proper connection between the two joining partners without damaging the backside of the sheet stack. Even minor changes in welding conditions can lead to bad results. To overcome this problem a camera based closed loop control for partial penetration welding of overlap joints was developed. With this closed loop control it is possible to weld such configurations with a stable process result even under changing welding conditions.

Keywords: laser welding; quality control; closed-loop control; partial penetration; cellular neural networks

1. Introduction

For many years the laser welded overlap joint with full penetration was one of the most common laser joining techniques in car body manufacturing. The process window was quite wide since a stable full penetration process worked in wide laser power range at a given welding speed. The transition to laser welded overlap joints with partial penetration on the contrary narrows the process window significantly. This is due to the fact that the laser power has to be adjusted very precisely to ensure a proper connection between the joining partners without damaging the bottom side of the welded sheet stack. However, in production environments it is quite difficult to ensure stable welding conditions. Several interference factors are influencing the process such as the fluctuating welding plume or degrading protective glasses that are influencing the laser power on the work piece itself or an unsteady welding speed caused by the combination of laser scanners and robot arms.

In former publications [1,2] a closed loop control system was presented. The latter allows the control of the laser power in a way that a stable full penetration in an overlap joint is maintained even under fluctuating welding conditions. This paper presents a closed loop control for partial penetration welding processes in overlap joints based on a Cellular-Neural-Network (CNN) camera that is derived from this system.

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2. Experimental Setup

The welding experiments were carried out with a 2D laser scanner setup. The laser source for the experiments is a 5 kW, 1030 nm Trumpf TruDisk 5001 Yb:YAG thin disk laser with a transport fibre with a core diameter of 200 μm. The laser scanner used – a Trumpf PFO-33 – was equipped with a 450 mm focusing optics which resulted in a focal diameter of 600 μm.

The CNN-camera system is adapted to the scanner optics through a 90° beam splitter. With it the camera perspective is coaxial to the laser beam. This allows an invariant field of view regardless of the scanner position. For the experiments a lens system consisting of three achromatic lenses was designed to achieve optical magnifications β between 1.5 and 3.0, see Figure 2. In combination with an optical band-pass filter in the near infrared spectrum, camera images with high quality can be obtained [3].

The complete image processing and also the calculation of the control signal are performed with the CNN-camera. The control of the laser power is done by a 10 V analog signal that is connected with the fast control input of the laser. The welding process is an overlap joint of two zinc coated steel sheets with a defined gap between the joining partners. The welding is performed without any shielding gas or filler wire.

2.1. Camera hardware

The CNN-camera used for the welding experiments is an Anafocus Eye-RIS v1.3 camera with the new Q-Eye chip [4]. The Q-Eye is a quarter CIF resolution fully programmable smart image sensor. It consists of 176 x 144 cells, each containing a processor merged with an optical sensor, memory circuitry and interconnections to the eight neighboring cells. This means that each pixel can both sense the corresponding spatial sample of the image and process this information in close interaction with other pixels.

Besides the Q-Eye focal plane processor, the Eye-RIS camera system consists of an additional FPGA based NIOS II processor by Altera to control the operation of the whole vision system and to analyze the information output of the Q-Eye chip performing all the decision-making and actuation tasks.

2.2. Algorithm

The image processing algorithm is designed to extract a dark area behind the bright area where the laser hits the work piece. This dark area, the so called full penetration hole (FPH), indicates that the keyhole has passed the interface of one of the joining partners. As shown in earlier works [5] the intensity image of the laser interaction zone is rather constant for a large range of laser power and feeding rates. Therefore, a global threshold is applicable to binarize the images acquired during the welding process. An example of binarized image is shown in Figure 1 left (a). In the following an algorithm to discriminate the full penetration hole by the execution of directional dilations is described [6]. Since it is based on basic local neighborhood operations [7], it can be implemented and efficiently run on any CNN architecture. Figure 1 left shows the result obtained executing dilation from the top – right corner to the bottom – left corner of the binarized image [8].

![Figure 1: Left: Dilation parallel to one diagonal. (a) is the source image; (b) shows the direction of the dilations; (c) is the result of the dilating operation. At the end, a logical XOR and a logical AND are applied in succession in order to keep white pixels in the dilated area only (d) [8]. Right: Image evaluation algorithm. The source image is at first binarized and then dilated along the image diagonal from the top-right to the bottom-left. The dilating result is masked at the end [8].](image-url)
The algorithm applies an arbitrary constant threshold value to the source image and performs a dilating operation along the image diagonal. Afterwards, logical operations are executed in order to keep white pixels in the dilated area only, as described in Figure 1 left. At the end, the mask is applied in order to hide the noise due to the dilation of the external interaction zone edges. The algorithm and the application of the masking operation take a single image processing time of about 42 µs. Figure 1 right clarifies the principle of the algorithm [8].

2.3. Control System

This paper deals with a system implementation for closed loop control; i.e. the CNN-camera system controls the laser welding machine. The available hardware therefore essentially consists of: the weld control system, a laser control unit (NC/PLC) and the laser. The laser control unit is responsible for safety interlocks, laser ON/OFF signals and movement. The laser power is controlled by an analog voltage between 0 and 10 V which corresponds to 0 - 100% of the laser power. The CNN control unit was built in order to receive a digital START/STOP signal from the laser control unit and to control the laser power according to the command signals received from the CNN-camera, see Figure 2. An additional PC with the control software is also part of the weld control system.

![Figure 2: Scheme of the weld control system and its integration into the infrastructure of the welding machine.](image)

3. Pre examination

In former publications like [3] it was shown that it is possible to reach and control a process state in an overlap joint that results in partial penetration where only the upper joining partner is fully penetrated. This is due to the fact that after the laser fully penetrates the upper sheet of the stack, a dark area behind the laser interaction zone is visible in the camera picture that looks quite similar to full-penetration.

Figure 3 shows the result of this behavior. One can see that the laser power is kept at the level where only the upper sheet is fully penetrated. Inset picture a) illustrates the shape that is seen by the camera at the lower power level when the laser beam partially penetrates the upper metal sheet, and inset picture b) shows the shape when full-penetration of the upper sheet is reached.
4. Experiments

The so called full penetration hole (FPH) is a well known image feature widely used for monitoring or closed loop control of laser welding processes [9, 10, 11]. Former experiments [1, 2, 3] demonstrated a closed loop control system that maintained the full penetration welding state with the use of this image feature. Figure 4 shows the scheme of a welding process in the full penetration state and the corresponding camera image with the FPH as the image feature used for the feed back in comparison to a welding process in the partial penetration state.

4.1. Possible working point areas

The principle of the control loop is described with Figure 5: When the line energy $S = P/u$ - where $P$ is the laser power and $u$ is the feed rate - is increased from the regime of heat conduction welding over the partial penetration to the state of full penetration, the probability $P_\text{FPH}$ to detect the image feature FPH behaves like in Figure 5. This
behavior is due to the fact that when the keyhole is piercing the bottom side of the upper sheet, there is no significant thermal light from the lower sheet since there is no keyhole in it. This leads to the appearance of the image feature FPH when passing the gap between the two sheets. From this chart it is obvious that there are three possible regions (marked as 1, 2 and 3) for a closed loop control.

The first region for a closed loop control, as described in earlier publications like [1,2,3], is at the rising edge of $\rho_{FPH}$ at a line energy between 50 J/mm and 60 J/mm, marked with “1”. The control strategy in this region is to increase the laser power if no FPH is detected and to decrease it if a FPH is detected. The result is a full penetration welding state.

The second region to establish a stable closed loop control is the rising edge of $\rho_{FPH}$ at a line energy between 20 J/mm and 30 J/mm, marked with “2”. In this region a partial penetration between the two joining partners is reached with the same control strategy as mentioned above. This leads to the result that is shown in Figure 3, where only a weak connection between the joining partners is reached.

The third possible region (“3”) is the trailing edge of $\rho_{FPH}$ between 35 J/mm and 40 J/mm. The control strategy for this trailing edge is exactly the opposite way to the one for the full penetration as mentioned above. If there is no FPH visible the laser power has to be decreased until the FPH becomes visible. This control strategy also leads to partial penetration state, but compared to the one on the rising edge, the penetration depth and connected area is significantly higher, due to the higher line energy.

Figure 5 Left: Chart of the probability $\rho_{FPH}$ to see the image feature (the so called “full penetration hole” FPH) from heat conduction welding 20 J/mm and below to full penetration 55 J/mm and above. Right: Detailed chart of the probability $\rho_{FPH}$ to see the image feature (the so called “full penetration hole” FPH) [1] in the camera image over the used line energy. The welding was performed with a ramping of the line energy at a welding speed of 5 m/min. Two 1 mm thick zinc coated steel samples with different size of the gap between the sheets were used. The line energy was ramped from heat conduction welding to partial penetration regime.

4.2. Visibility of the image feature

The visibility of the image feature “full penetration hole” FPH in the partial penetration state in working point area “3” is slightly worse compared to the full penetration state in working point area “1”, see Figure 6. The main differences are the contrast of the FPH to the surrounding process and the position and shape of the FPH. Nevertheless the algorithm described in chapter 2.2 offers very high detection rates in the region of 90% for both working point areas. This is due to its structure which is largely insensitive to the longitudinal position of the FPH and its robust threshold algorithm.
4.3. Welding results

As described above, the real-time control uses the “full penetration” quality feature FPH in the working point area “3”. Therefore, partial penetration - in particular the transition form the top to the bottom sheet - is detected by the presence or absence of the dark area behind the laser interaction zone, as described in previous chapters. The actuating variable used was the laser power. The advantages of this actuating variable are the high possible dynamics of up to 10 kHz for the Trumpf laser systems and the fact that it can be controlled by a simple analogue signal of 0 – 10 V corresponding to a laser power output of 0 – 100%.

Most of the experiments were performed with uncleaned work pieces to have a situation comparable to industrial production lines. This might lead in some cases to higher smoke residue and spatter ejection. The welded samples were zinc coated ZStE 340 steel.

Figure 6: Appearance of the image feature of the “full penetration hole” FPH in a partial penetration state in working point region “3” (upper row) compared to the appearance of the FPH in a full penetration state in working point region “1” (lower row).

Figure 7: Closed loop control of a partial penetration welding with a modulation of the welding speed between 6 and 7 m/min. The sheet stack was two times 1 mm zinc coated steel with a gap of 0.2 mm. From top to bottom: Longitudinal section of the seam, top view of the seam, bottom view of the heat trace, chart with the measured penetration depth in the lower sheet (magenta) and laser power over the length of the weld seam.
The parameters of the closed loop control system are set to maintain a $\rho_{\text{FPH}}$ of about 30%. This leads to a stable partial penetration with a line energy of about 40 J/mm for a welding speed of 5 m/min in 2 x 1 mm zinc coated steel, according to Figure 5 (right). This figure also implies that the resulting line energy is quite independent of the gap size.

Figure 7 shows the result of an experiment with a controlled partial penetration welding in a stack of 2 x 1 mm thick zinc coated steel with a gap of 0.2 mm. The welding speed varied between 6 and 7 m/min during the welding process. One can see that the closed loop control maintained the partial penetration state by adapting the laser power to the changing welding speed. The resulting penetration depth in the bottom sheet is slightly overcompensated by the closed loop control, but neither a loss of connection nor an unwanted full penetration occurred. The bottom view of the weld seam shows a heat trace on the zinc coating but no melting of the surface, which is a preferred result in car body manufacturing.

![Graph](image1.png)

Figure 8: Penetration depth in the bottom sheet and connection width (cross section) against the gap size between the joining partners. The sheet stack was two times 1 mm zinc coated steel with a different gap sizes between 0.05 mm and 0.33 mm.

To clarify the influence of a changing gap size during a controlled partial penetration welding process, an experiment with an increasing gap size between 0.05 mm and 0.33 mm during the process was performed. Figure 8 shows the resulting penetration depth in the bottom sheet and the cross section as a function of the gap size.

![Graph](image2.png)

Figure 9: Left: Penetration depth in the bottom sheet over the gap size for different feed rates. Right: Cross section against the gap size for different feed rates.
The closed loop control remains stable during welding with the changing gap size. Nevertheless the penetration depth as well as the cross section shows a dependency on the gap size. To reveal the dependency of the penetration depth and the cross section on the gap size and the welding speed further welding experiments with different welding speeds and gap sizes have been carried out.

As shown in Figure 9 (left) the penetration depth of the controlled partial penetration welding experiments suffer a variation that is mainly influenced by the feed rate. For lower feed rates e.g. 5 m/min the variation is slightly lower (sd = 0.049 mm corresponds to 15%) compared to higher speed like 7 m/min (sd = 0.096 mm corresponds to 18%).

However the cross section shows a rather low variation over the gap size and the welding speed as shown in Figure 9 (right). In fact the dependency on the gap size is clearly visible in Figure 9 (right) as well as in Figure 8, but the variation itself is significantly lower (10% compared to 18% at 7 m/min and 6% compared to 15% at 5 m/min). In the same way the dependency on the welding speed is still there, in a manner that the cross section increases with welding speed, but also with a clearly lower variation compared to the penetration depth.

5. Conclusion and Outlook

It could be shown that the concept of camera based closed loop control by using the image feature FPH is adaptable to partial penetration welding processes. The main differences for the image processing to find the image feature FPH are the lower contrast of the FPH and its slightly different shape. The control system was able to reach and maintain the regime of partial penetration even under changing welding conditions to ensure a proper connection between the joining partners without damaging the bottom side of the lower sheet. The variation of the cross section (standard deviation over mean value) in all experiments was better then 10%.

Further experiments are planned to enhance the stability of the closed loop control of partial penetration welding processes. Furthermore the algorithm for direction independent welding processes as described in [1, 2, 12, 13 and 14] will be adapted for the closed loop control of partial penetration.

The adaption on other materials like aluminium is already part of current research [15] and will be continued in future investigations.

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