Proc. of WESIC 2001, University of Twente, The Netherlands, 27-29 June 2001

PENETRATION FEEDBACK CONTROL IN OVERLAP LASER WELDING OF SHEET METAL

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Abstract

This paper deals with a method to control the penetration depth in overlap laser welding, using feedback control. Some applications demand that an overlap weld is joined sufficiently, while it is not fully penetrated to the back side of the bottom plate. An optical sensor which measures the process radiation coaxially is used as the feedback signal. First the correlation between the penetration depth and this optical signal has been obtained. Hereafter, system identification methods have been used to obtain a dynamic model of the welding process. The model is written as a transfer function with laser power as input and the sensor signal strength as output. With this model a simple feedback controller has been designed and tested in real experiments. The laser power serves as an actuator regulating the penetration depth. It was found that the feedback control system was able to maintain a certain penetration depth, within acceptable boundaries.

1 Introduction

Penetration depth is a very important quantity of a weld and generally the first property a weld is tested on. On-line feedback control of the penetration depth will stimulate laser welding applications in manufacturing processes. During laser welding, different optical signals are emitted from the weld-pool area, e.g. thermal radiation from the molten material, plume radiation and reflected laser power. The possibility to measure these emissions and to use them for monitoring and control purposes is examined by many authors e.g. (Sanders et al. 1997, Beersiek et al. 1997, Lankalapalli et al. 1999), among others. It was found that there exists a linear correlation between the penetration depth and coaxially measured optical signals emitted from the weld-pool area, during partial penetrating welding conditions. These examinations and the industry need to have on-line information about the welding quality, led to the introduction of several commercial monitoring systems for laser welding.

The objective in this work is to join two overlapping plates without actually penetrating the bottom plate, see figure 1, using a feedback control. The feedback system should be able to cope with sudden (welding) speed changes. In practice these speed changes may be the result from limitations of the manipulator system (e.g. robot or gantry system). To maintain high tracking accuracy, needed in laser welding applications, the manipulator often has to decelerate in front of corners and the sharp curves.

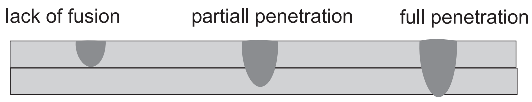

Figure 1: Three typical weld geometries: lack of fusion, partial penetrated and full penetrated weld.

In this paper two commercial monitoring systems are used, consisting of four sensors. The correlation between these sensor signals and the weld penetration depth is verified and used to control the penetration depth. To be able to design a compensator, the dynamic behavior of the laser welding process, during partial penetrating welding conditions, has been obtained using system identification techniques. With this dynamic model a controller has been designed and tested.

Feedback control with similar purpose has also been demonstrated by (Dahmen et al. 1999). They used a signal obtained from a coaxial mounted CCD camera to control the penetration depth.

2 Experimental set-up

A 2kW Nd:YAG laser (Haas 2006d) with an 0.6 mm optical fiber has been used to make the welds. Two 0.7 mm mild steel plates were welded together in an overlap configuration. Using a focusing lens with 100 mm focal length a 300 μm focused beam diameter was reached. The focal position of the beam was placed 0.1 mm under the surface of the top plate for optimal absorption. The optical emissions from the weld pool area were collected by two monitoring systems with a total of four detectors. The first system consists of one detector, which is positioned inside the laser device itself. This system is called the ”Weldwatcher” (Güttler 1998). It measures the plume intensity through the optical fiber in the opposite direction as the laser power is delivered to the work-piece, see figure 2. This sensor contains an internal low-pass filter.

The second monitoring system used in this research is of Jurca Optoelectronik GmbH (Kogel-Hollacher et al. 1998). This system has three detectors consisting of different optical filters in front of photodiodes. The three sensors are sensitive to different optical wavelength bands. This way the plume (400-800 nm), the thermal radiation (1100-1800 nm) and the reflected Nd:YAG (1064 nm) radiation from the process are measured separately.

Together with the x-y coordinates of the manipulator table and the laser power, the four sensor signals are recorded by a DSP system of dSpace at a sampling rate of 20kHz. The laser power is used to close the feedback loop and can be regulated by the DSP system. The dynamic response of the laser device to demanded power changes is discussed in section 4 .

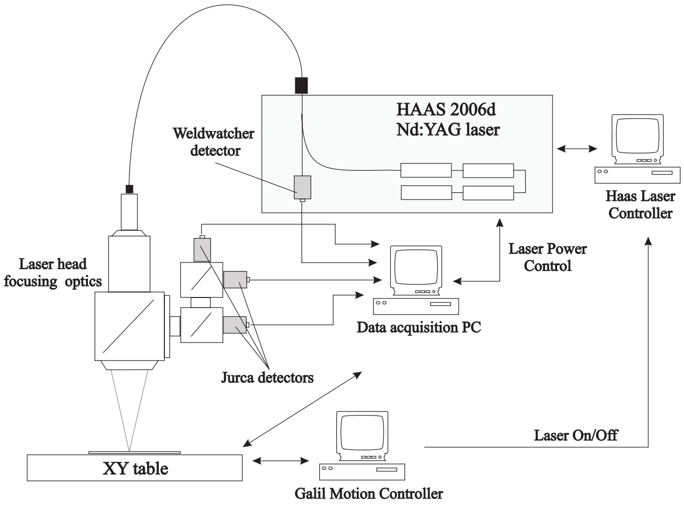

Figure 2: Schematic drawing of the experimental set-up, containing the laser device, the controllers and the welding monitoring systems

3 Sensor signal versus penetration depth

To be able to control the penetration depth during the overlap welds the relation between the sensor signals and the penetration depth has to be known. Therefore this relation has been investigated first. Overlap welds have been carried out at two welding speeds, 50 mm/s and 100 mm/s respectively. Laser power has been varied to achieve different welding depths. Cross sections of the different welds were made and from these the welding depths could be measured. The relation between the penetration

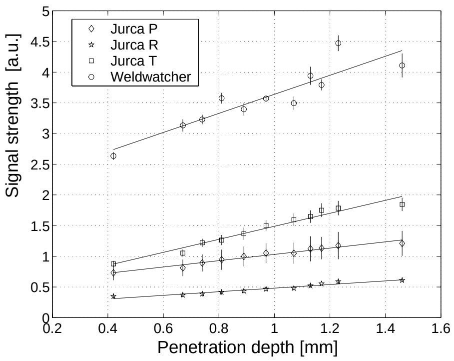

Figure 3: Relation between the sensor signal strength and the penetration depth at a welding speed of 50 mm/s

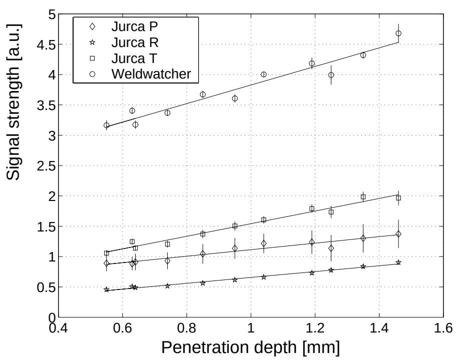

Figure 4: Relation between the sensor signal strength and the penetration depth at a welding speed of 100 mm/s

depth and the different sensor signals are shown in figure 3 and figure 4. The signal strength belonging to a particular welding depth has been obtained by averaging over of approximately 2000 samples (0.1 s) and the standard deviation is indicated with vertical bars in the figures.

It can be clearly seen that all the sensors show a linear correlation with the penetration depth. The standard deviations on the measured points are relatively low for all signals except for the Jurca P signal. Because the slope of the Weldwatcher signal is larger then all the other sensor signals, this sensor signal is selected to be used in the design of the feedback system. In this way the maximum resolution between penetration depth and sensor signal is reached. Moreover it can be seen, when comparing figure 3 with figure 4, that the correlation is dependent on the welding speed. At higher welding speed the signal is higher for a certain penetration depth. Although this speed dependence is small for the Weldwatcher signal it has been accounted for in the feedback system, see section 5.

4 System identification

Next the dynamic behavior of the process is investigated using system identification. In system identification a dynamic model is constructed by matching measured input and output data of a process as well as possible to this model (Ljung 1997). The model structure (type and order) has to be selected beforehand and is assumed linear. In our case the laser welding process is defined as the system with the asked laser power as an input and the measured Weldwatcher signal as an output.

The system identification is divided into two parts. First the dynamics of the laser device is investigated. This means that the dynamic relation between the asked and delivered laser power is determined. The second part of the process which has been identified, has the measured laser power as an input and the Weldwatcher signal as an output. This last part contains the actual welding process and the sensor dynamics. Afterwards these two models are combined into the complete process model.

4.1 Identification of laser device

A Random Binary Signal (RBS) has been used to excite the laser device in experiments. Because it was already known, from earlier experiments and documentation, that the bandwidth of the laser device would not exceed 1kH, the frequency content of this signal has been limited to frequencies up to 2kHz. The output signal in the system identification of the laser device is the measured (actual) laser power.

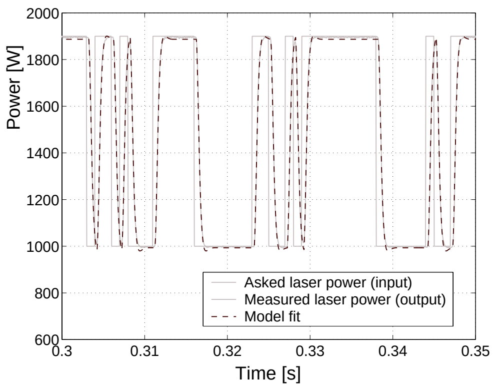

Figure 5: Measured input and output signal and best model fit for identification of the laser device

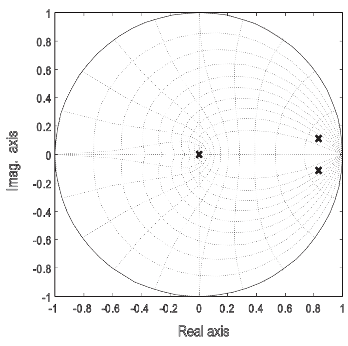

Figure 6: Pole zero map of the dynamical model of the laser device

In figure 5 the input and measured output signals of the laser device are shown, together with the best fit that was found with the system identification. The discrete model (sample frequency 20 kHz) found here is a second order model with a time delay of 0.3 ms (6 sampling periods). This time delay is a large part of the overall response time of the laser of approximately 1 ms. The discrete pole-zero map of the model is shown in figure 6, with one complex pole pair ($0.83 \pm 0.11i, \omega_n = 704Hz, \zeta = 0.803$) describing the dynamics and four poles in $z = 0$ to obtain a total of 6 samples delay (#delays = #poles − #zeros). The dynamics of the laser device most likely originates from the internal controller of the laser device.

4.2 Identification of welding process

The same experiments that where used to identify the laser device where also used to find a dynamic model of the welding process. In this case the model has the measured laser power as input and the measured Weldwatcher signal as output. Again an RBS signal was used to excite the system. The identification is carried out for a welding speed of 50 mm/s. A small time region of the measured input and output data used in the identification is shown in figure 7. The best matched model found is a fourth order

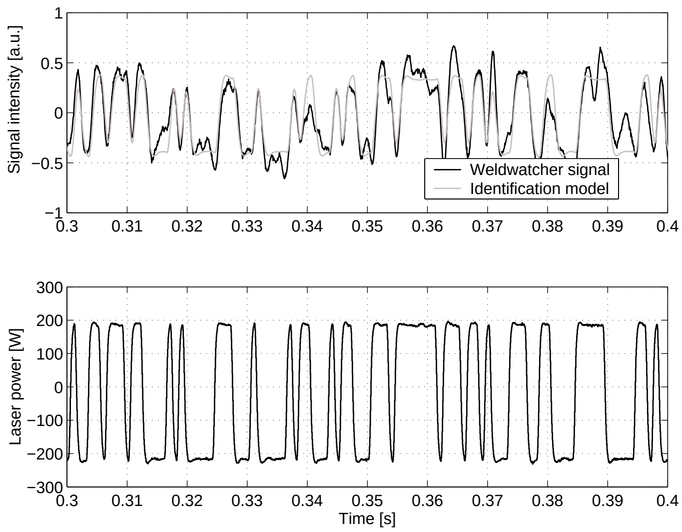

Figure 7: Results of the identification of the overlap laser welding process. The measured laser power as input for the identification is shown in the bottom graph. The output, which is the measured Weldwatcher signal and the identified model are shown in the top graph. The means have been removed from all signals!

model with 0.1 ms delay (2 sample periods), for which the response to the measured input signal is also shown in figure 7. The discrete pole-zero map of this model is shown in figure 8. It shows two complex pole pairs: ($0.91 \pm 0.08i, \omega_n = 401Hz, \zeta = 0.72$) and ($-0.47 \pm 0.46i, \omega_n = 7651Hz, \zeta = 0.17$) respectively. Furthermore a zero in $z = 1.41$ outside the unit circle is shown, indicating the presence of non-minimum phase behavior and a zero in $z = 0$, making sure a total of 2 samples delays is achieved. This last zero adds no dynamics to the system but is solely to complement the number of delays. The dynamics found for the process is probably mainly the dynamics of the analog low pass filter inside the Weldwatcher sensor, as mentioned in section 2.

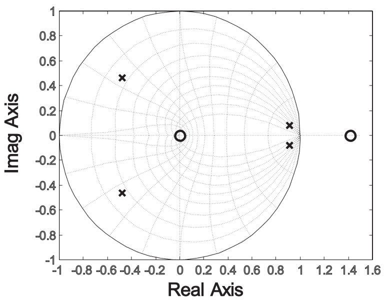

Figure 8: Pole-zero map of identified process model

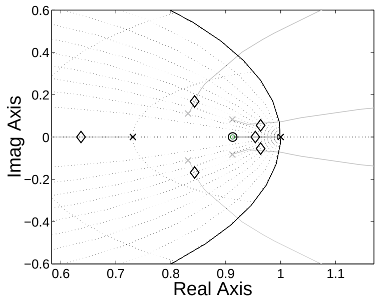

Figure 9: Root locus of process and compensator showing only the dominant poles and zeros

Apparently the bandwidth of this low pass filter is about the 400 Hz. Supporting this idea is the fact that identification made at higher welding speeds of 100 mm/s did not result in a different dynamics. The two complex pole pairs were found at the almost the same locations. Combining the model of the laser device with the model of the welding process leads to the following transfer function, with laser power as input and the Weldwatcher signal as output: :

$$H(z) = \frac{-6.08 \times 10^{-6} z^{-8} + 8.60 \times 10^{-6} z^{-9}}{1 - 2.54z^{-1} + 1.71z^{-2} + 0.13z^{-3} + 0.06z^{-4} - 0.62z^{-5} + 0.26z^{-6}}$$

5 Feedback control design and results

The design of the compensator is done in the discrete time domain. Objective is to keep the controller fast enough to respond to changes in welding speed and make it robust for other disturbances like possible nonlinearities in the process. To make sure no end error occurs, a PI compensator was implemented. Therefore a pole was placed in $z = 1$ and a zero in $z = 0.913$, on the real axis. To suppress high frequency process and measurement noise an addition pole was placed in $z = 0.731$. It turned out that without this last pole the process was influenced to much by the measurement and process noise. The gain of the controller was initially set to 40, resulting in a bandwidth of approximately 150 Hz. The transfer function of the compensator is: $C(z) = \frac{40.1(z-0.913)}{(z-1)(z-0.731)}$. This compensator has been implemented and tested in real experiments.

In experiments it turned out that the bandwidth of 150 Hz was too high to obtain a smooth process. The response of the system was very fluctuating (not unstable!) and irregular weld surfaces were obtained, which is not a good quality of a weld. During the experiments the gain was reduced to lower the bandwidth. Hereby the response of the controller was less fluctuating and a smooth weld surface was achieved. However a too low bandwidth would lead to a too slow response. A gain of 10 for the compensator was finally chosen, leading to a closed loop bandwidth of approximately 35 Hz.

The complete feedback system is schematically shown in figure 10. The relation between the penetration depth and the Weldwatcher signal, see figure 3 and 4, is used to generate a reference signal. Since this relation is also speed dependent, the speed is also an input in the reference generator. It is assumed that speed influences the signal to depth relation linearly.

The performance of the feedback system is tested by applying sudden changes in welding speed. As a reference a longitudinal section of an experiment without control

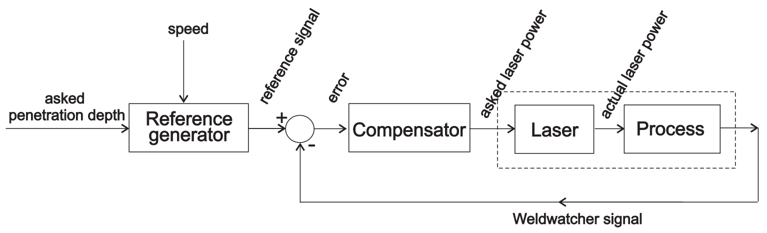

Figure 10: Schematic drawing of the feedback set-up

is shown in figure 11, indicating the penetration depth of the weld along the welding direction. A constant laser power of 1100 W is applied. In this and all other experiments the welding speed was suddenly decreased from 100 mm/s to 60 mm/s at 46 mm from the start of the weld. As can be seen from the longitudinal section at the slower speed the weld penetrates the bottom plate. After the speed chance the average Weldwatcher signal is clearly higher. This higher signal at lower speed indicates a deeper penetration.

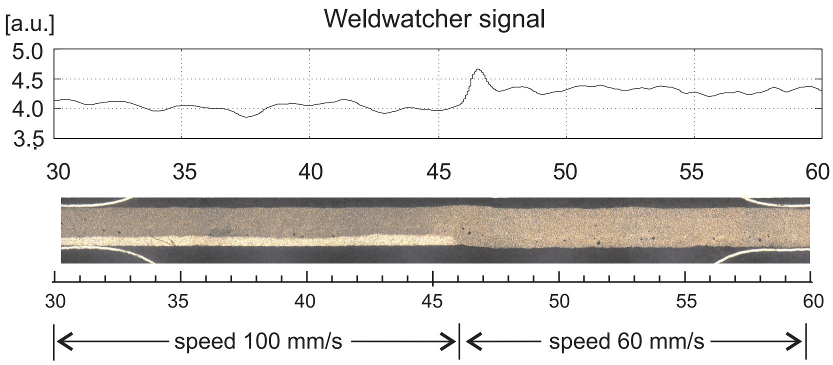

Figure 11: Longitudinal section of an uncontrolled experiment together with the corresponding Weldwatcher signal, which is low pass filtered at 20 Hz. A constant laser power of 1100W was used. Here the material used for the embedding of the sample is black, the weld is the dark grey area and the base material is visible as the light grey part

In figure 12 the laser power and Weldwatcher signal of a controlled experiment are shown. The feedback control system was active between 15 mm and 85 mm. In this experiment the desired welding depth was set to 1.125 mm, resulting in an reference signal of 4.02 for 100 mm/s and 3.86 for 60 mm/s, respectively. Clearly the controller diminishes the laser power at the lower speed. A longitudinal section of the weld belonging to this experiment is given in figure 13. Obviously, the weld has not penetrated the material and the penetration depth is maintained close to the desired level. However it can be seen that the penetration at the lower speed is slightly deeper and some small fluctuations are present in the penetration depth. But these are within acceptable boundaries of the objective.

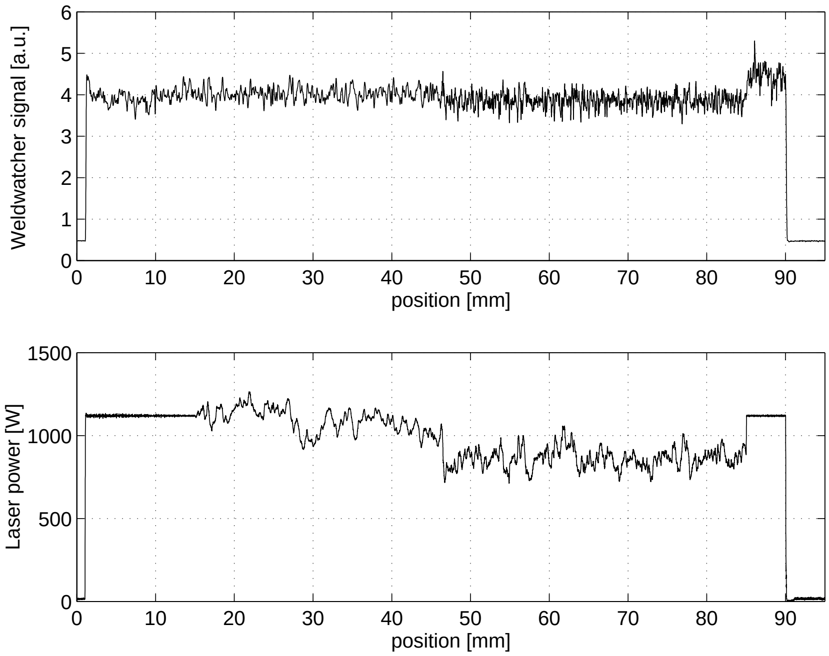

Figure 12: The response of the feedback system to a speed change from 100 mm/s to 60 mm/s at 46 mm. The asked welding depth was set to 1.125 mm, resulting in a reference signal of 4.02 and 3.86, respectively

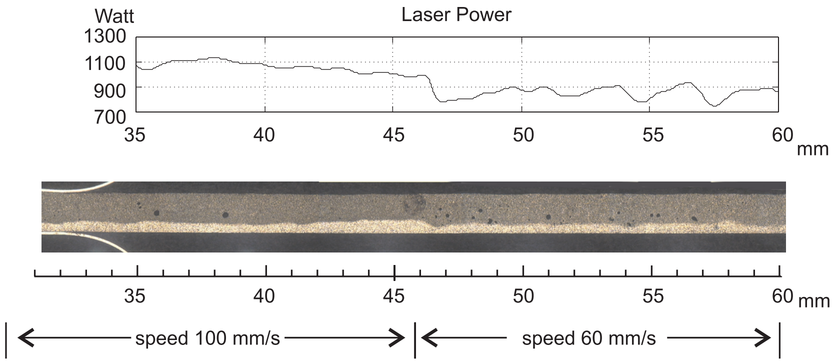

Figure 13: Longitudinal section of a controlled welding experiment and the corresponding laser power (actuator signal), which is low pass filtered at 20 Hz. The asked welding depth was set to 1.125 mm. Here the material used for the embedding of the sample is black, the weld is the dark grey area and the base material is visible as the light grey part

6 Conclusions and discussion

A linear relation between the sensor signals and the penetration depth was found experimentally. This linear relation is slightly dependent on the welding speed. With the use of system identification a dynamic model has been constructed of the laser welding process, with as input the laser power and as output the sensor signal strength. This model has been used to design a compensator for feedback control. With a bandwidth of 35 Hz for the feedback, good quality welds were achieved. The feedback system was able to maintain a certain penetration depth, within acceptable boundaries, during experiments with sudden welding speed changes.

Parameters, such as focal position and shielding gas, were kept constant in this investigations. In practical applications these may be hard to keep constant and therefore their influence should be investigated.

7 Acknowledgement

This research was carried out under project number MC 8.98058A in the framework of the Strategic Research programme of the Netherlands Institute for Metals Research in the Netherlands (www.nimr.nl).

References

Beersiek, J., Poprawe, R., Schulz, W., Gu, H., Mueller, R. & Duley, W. (1997). On-line monitoring of penetration depth in laser beam welding, *Proceedings ICALEO '97* pp. 30–39.

Dahmen, M., Kaierle, S., Abels, P., Kratzsch, C., Kreutz, E. & Poprawe, R. (1999). Adaptive quality control for laser beam welding, *Proceedings ICALEO '99* pp. 29–38.

Güttler, R. (1998). Sensor detects faults in the keyhole, *Opto& Laser Europe* p. 13.

Kogel-Hollacher, M., Jurca, M., Dietz, C., Janssen, G. & Lozada, E. F. D. (1998). Quality assurance in pulsed seam laser welding, *Proceedings ICALEO '98* pp. 168–177.

Lankalapalli, K., Tu, J., Leong, K. & Gartner, M. (1999). Laser weld penetration estimation using temperature measurements, *Journal of Manufacturing Science and Engineering* **121**: 179–188.

Ljung, L. (1997). System identification toolbox user guide, *The MathWorks Inc.* .

Sanders, P., Keske, J., Kornecki, G. & Leong, K. (1997). Capabilities of infrared weld monitor, *Proceedings ICALEO'97* pp. 1–10.