Process Control of Stainless Steel Laser Welding using an Optical Spectroscopic Sensor

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Abstract

The in-process monitoring and real-time control of the penetration depth during laser welding is evaluated. An optical collimator collects the optical emission for measurement with a fast spectrometer. The sensor data are used to calculate the electron temperature and subsequently to determine the weld quality of overlap welds in AISI 304 stainless steel sheets performed both with CW Nd:YAG and CO\textsubscript{2} lasers. A PI-controller adjusts the laser power aiming at a constant penetration depth and has been tested for Nd:YAG laser welding. Optical inspection of the weld verifies the results obtained with the proposed closed-loop system of spectroscopic sensor and controller.

Keywords: laser welding process control; laser power setting; plasma emission spectroscopy

1. Motivation / State of the Art

The analysis of the plasma plume spectra emitted during the laser welding process is a promising technique to monitor and eventually to control the quality of the resulting weld seams [1]. It is well-known that the real-time identification and classification of weld defects has proven to be non-trivial and usually it is performed by means of statistical studies of intensity of the emitted process light in one or more selected wavelength ranges [2, 3, 4]. Alternatively, the analysis of the complete spectra makes it possible to measure specific emission lines which reveal more information about the welding process. The subsequent estimation of the electron temperature $T_e$ can be correlated with the quality of the corresponding weld seam. Sibillano \textit{et al} [5] showed a clear relation between the electron temperature signals and the penetration depth. In their work a CO\textsubscript{2} laser has been used. In case of pulsed and continuous-wave (CW) Nd:YAG lasers it is still debated if a plasma plume is generated during the process, even though several experimental investigations support this hypothesis [6].

The aim of this work is to demonstrate that the electron temperature signal calculated both during CO\textsubscript{2} and Nd:YAG laser lap welding processes can be successfully used for monitoring and control the penetration depth in real-time. In section 2 the hardware and software of the set-up are outlined. Next results from preliminary
experiments are reported, which are used to determine the setting of the process controller. Finally, the performance of the closed-loop system applied to the Nd:YAG set-up is evaluated.

2. Experimental Setup

The welding tests have been carried out by using a Nd:YAG laser (Trumpf THL4006D) and a CO₂ laser (Rofin Sinar DC025), which are both continuous wave (CW) lasers. The welding experiments have been performed in overlapped configuration of 1.3 or 2 mm-thick upon 2 mm-thick AISI304 stainless steel plates. The welding speed has been kept constant at 60 mm/s and 50 mm/s respectively.

The experimental setup for Nd:YAG welding is given in figure 1 left. For Nd:YAG welding the quartz collimator had a focal length of 200 mm. The optical plasma emission was collected with a collimator that was connected to a spectrometer (Ocean Optics HR2000+). The collimator was focused onto the weld pool at an incident angle of 65°.

For CO₂ welding, the plasma optical emission was collected by a quartz collimator of 6 mm focal length and sent, through a bifurcated optical fiber with 200 μm core-diameter, to a Si-PIN photodiode (320-1000 nm spectral range) and a HR2000+ spectrometer. Preliminary welding tests have been carried out aiming to investigate the influence of the observation angle and the relative position of the light collecting system with respect to the laser irradiated zone, on the morphology of the acquired plasma optical spectra. The collimator was placed at several observation angles and two different positions (side and front) with respect to the travel direction of the laser beam. For all the cases investigated, the acquired spectra did not show any significant difference. Only slight discrepancies were found, mainly related to the relative intensity of the continuous background or of the lines of the spectrum belonging to the shielding gas. Therefore the electron temperature measurement was not affected by the observation angle of the collimator. This setup is given in figure 1 right.

Spectrometer specifications for both of the experimental setup are supplied in table 1.

Argon shielding gas has been applied for both of the experimental setups. The focusing head is equipped with suitable nozzles providing an inert gas flow onto the laser metal interaction zone in order to prevent the weld seam from oxidation and avoid damaging of the focusing optics. The determination of the electron temperature $T_e$ is done using the well-known Boltzmann plot technique and assuming the local thermo-dynamic equilibrium (LTE) [4].

$$\ln \left( \frac{I_k A_k}{g_k A_k} \right) = - \frac{1}{kT_e} E_k + C$$  (1)
where $C$ is a constant and $I_k$ is the relative intensity of the emission line of the wavelength $\lambda_k$ (nm), $g_k$ is the statistical weight of the upper excited energy level with the energy $E_k$ (cm$^{-1}$), and $A_k$ (s$^{-1}$) is the transition probability for spontaneous radiative emission taken from the NIST database.

The electron temperature signal is used by a digital PI controller to adjust the laser power $P$ in real-time. The discrete time formulation of the controller is given as following

$$P(t_k) = P(t_{k-1}) + K_p \left[ 1 + \frac{\Delta T}{T_i} \right] \Delta T_e(t_k) - \Delta T_e(t_{k-1})$$

In equation 2 $P(t_k)$ is the controller output calculated by controller parameters proportional gain $K_p$ and integration time parameter $T_i$. The electron temperature error $\Delta T_e$ is steering the process to stabilize at a desired electron temperature set point. The controller is applied to Nd:YAG laser welding process with variable time step. The minimum sampling time is observed to be around 5 ms.

Table 1. Spectrometer hardware specifications for Nd:YAG and CO$_2$ welding

<table>
<thead>
<tr>
<th>HR2000+ Spectrometer Specs.</th>
<th>Nd:YAG</th>
<th>CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance slit</td>
<td>5 µm</td>
<td>5 µm</td>
</tr>
<tr>
<td>Diffraction grating</td>
<td>400 mm$^{-1}$</td>
<td>600 mm$^{-1}$</td>
</tr>
<tr>
<td>Range</td>
<td>400-586 nm</td>
<td>390-525 nm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.13 nm</td>
<td>0.12 nm</td>
</tr>
<tr>
<td>Minimal sample time</td>
<td>~ 1 ms</td>
<td>~ 1 ms</td>
</tr>
</tbody>
</table>

3. Process Characterisation

The Nd:YAG process behaviour is characterised with two experiments. In a first experiment the relation between laser power and penetration depth is investigated. The longitudinal cross-section along the weld in figure 2 right shows the varying penetration depth in an overlap weld of 2+2 mm sheets while the laser power is steadily increased and later decreased. Secondly, in a the same experiment the spectra are recorded and the Cr(I) electron temperature is calculated. As also shown in figure 2 right, a relation between the laser power and electron temperature is observed, which implies a relation between the electron temperature and penetration depth as well.

Figure 2. Left: Cr(I) electron temperature, calculated with 459.139-495.481 nm couple of emission lines, and laser power as functions of time with varying laser power. Right: Longitudinal cross-section of a weld with increasing and decreasing Nd:YAG laser power (700W -3200 W - 700 W).
Parallel investigations have been performed with a CO₂ laser source. Here, a 2 mm penetration depth was chosen as the desired value, corresponding to the full penetration of the upper sheet (1-mm-thick) and half penetration of the bottom sheet (2-mm-thick). In fact, a partial penetration depth is often required for most overlap joint industrial applications where the weld must not be visible from the bottom size of the product. On the other hand, the welded joint has not to be too shallow otherwise the mechanical properties of the welding product could be affected. The optimal CO₂ laser power value providing in our experimental conditions a 2-mm deep lap-joint has been found to be 1.2 kW at a travel speed of 50 mm/s. A full penetration over the 3mm thick samples was achieved for 1.7 kW incident laser power. In order to test the response of the sensor upon a dynamic change of the process conditions we ramped up and down the laser power from 1.7 kW to 1.2 kW within the same weld seam. The electron temperature has been calculated in real-time measuring the intensities of selected Cr(I) and Fe(I) spectral lines. Figure 3 shows the Fe electron temperature signal behaviour and the corresponding value of the penetration depth evaluated by metallographic analyses of the welded joint cross sections. In case of CO₂ laser welding processes, as far as the laser power and the penetration depth increase, a decrease of the electron temperature signal was measured. A possible explanation could be that as far as the keyhole becomes deeper, as a consequence of the higher power, the plasma plume above the work piece surface goes deeper into the keyhole itself along its axial direction. Under these conditions, the light emitted by the hottest core of the plasma plume is not anymore collected by the collimator, whose angle of view remains fixed during the experiments and mainly points onto the region above the keyhole. Therefore, it could be argued that the light detected by the sensor comes mainly from the external and colder shell of the plasma plume. For these reasons a lower electron temperature is measured.

The observed quantitative relationships between electron temperature and penetration depth are needed to implement the closed-loop control of the depth penetration.

Figure 3. Fe(I) electron temperature signal behaviour calculated with 517.09-421.91 couple of emission lines, in Ar atmosphere with variable laser power (1.7-1.2-1.7 kW power ramp).

4. Closed Loop Penetration Depth Control

In a closed-loop experiment the parameters of the PI-controller have been set to achieve a control bandwidth of 10 Hz. Tests have been performed with Nd:YAG laser welding in an overlap configuration of 1.3+2 mm sheets by
using a reference value for the electron temperature of 6850 K, which should result in a partial penetration of the lower sheet. The experiment started with a high laser power value of 2900 W which is kept constant for 200 ms after which period the controller is enabled. Figure 4 shows the recorded laser power and electron temperature. Initially, the constant high laser power corresponds to a rather high electron temperature of about 7150 K which is above the desired set point. As soon as the controller is enabled, the laser power is indeed controlled such that the electron temperature fluctuates around the given set point of 6850 K.

In the same figure the penetration depth is depicted by bars with two bullets on each end. The height of each bar indicates the measured penetration from the transversal cross section and the value of the penetration depth is given as well on the right side of the full bullet. The thin dashed line is the height of the top plate of 1300 μm.

The transversal cross sections of the weld in Figure 4 show that second plate penetration is present in the early two sections, from which it is expected that the penetration depth is also quite stabilised near section 2. The section 3 of the transversal cross section set indicates the existence of the gap between the two plates. This results the controller to lose the lower plate penetration, section 4. Later, the controller is observed to stabilize the penetration depth throughout the weld which could be seen by sections 5 and 6.

![Figure 4. Top: Closed loop response of laser power and electron temperature and penetration depth with a controller stabilising the latter at 6850 K for Kp = 0.4 and Ti = 10 with 1250 l/h argon flow Bottom: Six transversal cross section of controlled welding process for 1.3 + 2 mm configuration](image)

The second case studied consists of the same setup as previously but for this case with slight change in Argon shielding conditions. The argon flow is increased from 1250 l/h to 1500 l/h value to obtain better surface look. On the other hand in particularly T_e range drops quite significantly compared to the previous set. The controller behaviour for this typical parameter set is observed in figure 5. Note that the same parameters, especially an uncontrolled 2900W laser power starting results with a lower T_e value and causing the controller to stabilize into a
lower power average of about 1300W to 1400W. This show how sensible a process can react on slight changes and that high control of all parameters is important. A lower penetration depth is achieved comparing the penetration depth with the previous experiment. For this case the penetration is limited to the first plate with a keyhole welding mode observed in all cross sections. Transversal cross sections proved that keyhole welding persists without changing back to the conduction mode.

As a third example, the controller is employed to stabilize melt movement inside a weld keyhole with a lower set point of 6825 K. The other experimental conditions are kept the same with the first set with the argon shielding is set back to the initial value of 1250 l/h. It is expected that the lower set point for the controller of 6825 K will result in a lower penetration. At the beginning coloring at the back side of the plates showed a full penetration to the first plate. Later the power level is stabilized in slightly lower power level in average around 1280 W. This made the controller to stabilize in to top plate with a shallow penetration. In section 3 of the cross section set the weld turned into conduction mode however later keyhole welding obtained. Controller is observed to stabilize the power value causing humps and drop-outs [8] on the surface.

It can be concluded that the set point is highly depending on the experimental conditions therefore it must be characterised for each set of experiments for this way of $T_e$ calculation.
5. Discussion and Conclusion

We have characterized the weld process to indicate the relation between penetration depth to the electron temperature for Nd:YAG and CO₂ laser sources. We consider the use of the electron temperature calculated from spectral measurements for the control of the penetration depth in overlap welds with both laser sources.

This signal appears to be suited for a controller that adjusts the laser power in order to maintain a pre-set penetration depth. We have successfully demonstrated a PI controller could be used to stabilize the observed electron temperature near its set point during Nd:YAG laser welding even though the measurement fluctuate because of the well-known instability of keyhole welding. Transversal cross sections for each experiment indicated the relation with the penetration depth.

Argon shielding condition is found to be crucial for control. For higher argon flow rate the sensor signal is less sensitive. At the same time sufficient shielding gas must be applied in order to assure a good quality of the top weld surface.

The weld pool instabilities introduce high frequent perturbations into the control input. By setting a proper control bandwidth, low pass filtering is obtained while the closed loop response is still reasonably fast.

During the controller experiments with a Nd:YAG laser it was found that the computed electron temperature depends not only on the penetration depth, but is also sensitive to the configuration of the shielding gas and the presence of a gap between the plates. For this reason the relation signal and penetration depth should be identified every time by process characterisation. Improvements of the spectral analysis are expected to make the control system more reliable and robust.

Future research will be directed towards the application of this controller into a CO₂ laser source.
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References