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Optical plasma spectroscopy as a tool for monitoring laser welding processes

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Methodology of research

ABSTRACT

Purpose: In this work we present experimental results of the joint application of the two previously mentioned spectroscopic techniques (electron temperature and correlation analysis) to a real-time laser welding monitoring case study. The two signals have been calculated starting from selected chemical species composing the plasma spectra. Experimental evidence is given of the correlation between the recorded signals and the occurrence of weld defects intentionally generated by varying the laser power and the travel speed.

Design/methodology/approach: An optical sensor prototype was used, that embeds a fiber-coupled miniature spectrometer having a dynamic spectral range from 390 nm to 580 nm and a resolution of 0.3 nm. Such a prototype employed data acquisition and real-time spectra analysis algorithms for both the previously mentioned spectroscopic techniques, e.g. the electron temperature and the correlation coefficients. A high power CO2 laser source was used with maximum output power of 6 kW. The laser-metal interaction zone was shielded by an argon flow. The plasma optical emission was collected by a quartz collimator and transmitted to the optical sensor by a 50 μm core-diameter optical fiber. Spectral lines from three different chemical species (Mn(I), Fe(I), Cr(I)) composing the plasma plume and the stainless steel alloy were used for the acquisition of the electron temperature and the correlation signals [1].

Findings: Compared to other optical sensors, the main advantage of this system is that it has a great flexibility upon variation of the welding metal or the joint geometries. In fact once the chemical composition of the alloy was known and most plasma emission lines are identified, only a slight calibration of the software settings is necessary.

Practical implications: A patented commercial version of this sensor (TRWOC from T.E.R.N.I. Research) is already available on the market. The capability of identifying the cause of the defect, once it has been detected is still limited to specific cases. Future work will regard the "intelligent" fusion of various sensor technologies aiming to increase the reliability of the system and, hopefully, realize a flexible and robust closed-loop control of the laser welding process.

Originality/value: Being known the emission line parameters, this method is particularly advantageous because it does not require too many calculations and can be easily implemented in suitable software for real-time temperature measurement.

Keywords: Laser welding; Plasma diagnostics; Optical sensor

1. Introduction

Laser welding is a highly automated process that is progressively more and more employed in the automotive industry. The advantages of laser welding include high speed, deep penetration, high aspect ratio of the joints, and low thermal distortion. One of the main disadvantages still preventing further expansion of this technology is the large number of parameters involved, that make the process complex to be handled in an industrial environment. To further improve the efficiency of the laser welding systems, quality assurance measures are increasingly required directly into the production processes. Traditional off-line inspection of welds is expensive, reduces productivity and requires dedicated test equipment and personnel. Therefore the development of automated on-line monitoring sensor for laser welding defect detection, and closed loop control systems, have been an open field of research in the last years. Several solutions have been proposed for the detection and prevention of welding defects. Among these, optical sensors, based on the detection of the plasma plume emission, the thermal radiation of the weld pool and the reflected laser light, have shown promising results [16].

We focused on the study of the laser-induced plasma plume generated above the weld pool during the process, since it plays a fundamental role in coupling the laser radiation to the material. Extensive studies have been conducted on the analysis of plasma optical emission because it is readily observable for being outside of the keyhole and can be easily collected with optical fibers. Monitoring of its light intensity, integrated over one or more spectral regions, is a common method of diagnostics and yields information on the presence of defects and on the depth of penetration. A number of quality monitoring systems based on one or more photodiodes have been reported by several authors [4,9].

Other research groups tried to find a correlation between the amplitude fluctuations of the photodiode signal and the weld quality. A stable signal was expected to correspond to a steady and reliable process while oscillations at determined frequency bands were supposed to correspond to wrong process parameters leading to weld defects [2,19].

Spectroscopic analyses of the plasma plume optical emission have shown unique capabilities for application on monitoring of laser welding processes. Like the previously mentioned photodiode-based sensors, spectrometers are non-intrusive, low cost and easy to embed in a production line, but they give much more detailed information on the plasma plume dynamics. Furthermore, thanks to the recent developments in detectors technology, fast spectrometers with acquisition rates up to 1 KHz are available, making these systems suitable for real-time industrial process monitoring and control. In spite of this, the development of a reliable and robust on-line welding sensor based on plasma spectroscopy is still an active area of research.

Plasma optical spectra are characterized by several emission lines of the excited atoms or ions belonging to the metals to be welded or to the gaseous environment (shielding gas or ambient air). It is thus possible to determine the chemical composition of the plasma. Furthermore qualitative variations of specific spectral features may be an indicator of a change in operating conditions that may induce a weld defects. In a previous work [13] we focused on the detection of shielding gas flaws and the formation of surface oxide layers on aluminium alloy laser welded butt-joints. Several optical spectra were acquired and investigated using different gas delivery systems, and changing the gas flow rate and the nozzle stand-off distance. Experimental results showed that in case of defective gas shielding there was an increase of the intensity of existing emission lines or the appearance of new ones belonging to the surrounding contaminant ambient air or to highly volatile alloying elements. This behavior was correlated to the seam oxidation or to a significant loss of alloying elements, both detrimental to the mechanical properties of the joints. Unfortunately a qualitative analysis of the optical spectrum that is strongly influenced by the working conditions, is often unreliable and thus not suitable for effective industrial process monitoring, even though it may be useful to monitor particular aspects of the welding process.

As it will be shown in the following section, starting from the optical visible spectra of the welding plasma it is possible to calculate important physical parameters of the plume like its electron temperature, electron density and absorption coefficient to the laser wavelength. This parameters have been demonstrated to be related to the stability of the laser welding process [1,3], and, especially the plasma electron temperature and its electron density, have been found to be highly correlated to the quality of the laser welded joints. A wide range of weld defects, such as lack of penetration, weld disruptions, crater formation and seam oxidation was successfully detected by monitoring the electron temperature signal [1,6,7,10,11,17,18].

Recently a further method was developed to analyze the laser welding plasma optical spectra, aiming to find a relationship between plasma dynamics and welding quality. It is called Covariance Mapping Technique (CMT) [12,14,15]. Experimental results showed that CMT can be reliably employed to better understand the physical interactions inside the plasma plume and the influence of the variation of the main process parameters on the weld quality. However, CMT requires quite a long acquisition and computation time, therefore it cannot be used for real-time applications. Nonetheless, once a preliminary study points out the most significant correlations, couples of spectral lines can be selected whose correlation coefficient can be real-time monitored during the process.

In this work we present experimental results of the joint application of the two previously mentioned spectroscopic techniques (electron temperature and correlation analysis) to a real-time laser welding monitoring case study. The two signals have been calculated starting from selected chemical species composing the plasma spectra. Experimental evidence is given of the correlation between the recorded signals and the occurrence of weld defects intentionally generated by varying the laser power and the travel speed.

2. Theory

The laser induced welding plasmas are generally supposed to be optically thin and in local thermal equilibrium. This means that inside the plasma volume the governing mechanisms for energy transfer among particles are collisional processes over radiative ones, so that it can be assumed that atoms and ions follow a Maxwellian energy distributions. In order to fulfill this criterion the electron density must overcome a critical threshold which may be slightly different according to the laser wavelength and the welding metal alloy [5]. Experimental investigations, based on the measurement of the spectral broadening of selected emission lines, have shown that typical electron densities in laser welding plasmas exceed this threshold by at least two orders of magnitude, so the local thermal equilibrium hypothesis is assumed to be valid.

The plasma electron temperature can be calculated by using the Boltzmann plot method. It consists in measuring the relative intensities of several emission lines [8], free from self-absorption, of a chosen chemical species of the optical spectrum. The optical intensity I_{mn} of the generic emission line associated with the transition from the upper energy level E_m to the lower energy level E_n is related to the energy of the emitted photons hc/λ_{mn}, the transition probability A_{mn} and the population of the excited state N_m by the following Equation:

$$I_{mn} = N_m A_{mn} hc/\lambda_{mn} \tag{1}$$

Assuming a Boltzmann statistics for the energy levels populations, N_m can be expressed as

$$N_m = (N/Z) g_m \exp(-E_m/kT) \tag{2}$$

where N is the total density of the states, g_m is the statistical weight of the energy level, and Z is the partition function. From Equations 1 and 2:

$$\ln\left(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}\right) = \ln\left(\frac{Nhc}{Z}\right) - \frac{E_m}{kT_e} \tag{3}$$

By plotting the first term of Eq. 3 versus E_m for several lines of the same chemical species, one can estimate the electron temperature Te, which is related to the slope of the linear fit [7,10,17].

The electron temperature can be directly estimated by use of the intensity ratio of just a couple of emission lines (labeled (1) and (2) in the following Equations) among those selected for the Boltzmann plot:

$$\frac{I(1)}{I(2)} = \frac{A(1)g_m(1)\lambda(2)}{A(2)g_m(2)\lambda(1)} \exp\left[-\frac{E_m(1) - E_m(2)}{kT_e}\right] \tag{4}$$

Extracting Te from Eq. 4:

$$T_e = \frac{E_m(2) - E_m(1)}{k \ln\left[\frac{I(1)A(2)g_m(2)\lambda(1)}{I(2)A(1)g_m(1)\lambda(2)}\right]} \tag{5}$$

Being known the emission line parameters, this method is particularly advantageous because it does not require too many calculations and can be easily implemented in suitable software for real-time temperature measurement [1,3].

The CMT is based on the assumption that the acquired spectrum can be considered as a sampling function for the signal coming from the detector. Under this hypothesis, if $x_k(\lambda_i)$ is the optical intensity recorded at the wavelength λ_i of the k_{th} spectrum, the covariance matrix of a series of N spectra is given by:

$$C_{ij} = \frac{1}{N}\sum_{k=1}^{N} x_k(\lambda_i) x_k(\lambda_j) - \left[\frac{1}{N}\sum_{k=1}^{N} x_k(\lambda_i)\right]\left[\frac{1}{N}\sum_{k=1}^{N} x_k(\lambda_j)\right] \tag{6}$$

The covariance matrix is clearly symmetric upon exchange of i and j. The normalized form of the matrix is generally used:

$$m_{ij} = \frac{C_{ij}}{\left(C_{ii} \cdot C_{jj}\right)^{1/2}} \tag{7}$$

In this way the values of m_{ij} lie in the range between -1 and 1, and the diagonal elements m_{ii}=1 (obviously, each chemical species is fully correlated with itself). Covariance values close to 1 indicate correlated pairs of species, whereas matrix elements equal to -1 denote anti-correlated pairs. A positive correlation value between two chemical species present in the spectrum, identified by their emission wavelength, indicates that they change, as a function of a known parameter, i.e. that they were formed by a process which had a similar characteristic. On the other hand, a negative correlation signifies that the two species are formed by competing processes. In case of non-correlation the species evolve through unrelated mechanisms and nothing can be really argued.

Since CMT requires quite a long acquisition and computation time, as mentioned in the previous section, single elements m_{ij} of the matrix, corresponding to selected couples of spectral lines, have been considered in the following paragraphs. The evolution of their correlation coefficient has been used for real-time monitoring purpose. Only the values of m_{ij} corresponding to a confidence level above 95% was taken into account. The threshold value fulfilling this criterion depends only on the number of spectra used for the correlation coefficient calculation.

3. Experimental setup and procedure

An optical sensor prototype was used, that embeds a fiber-coupled miniature spectrometer having a dynamic spectral range from 390 nm to 580 nm and a resolution of 0.3 nm. Such a prototype employed data acquisition and real-time spectra analysis algorithms for both the previously mentioned spectroscopic techniques, e.g. the electron temperature and the correlation coefficients. Field tests have been carried out in a real industrial production line of laser-welded stainless steel tubes. A high power CO_2 laser source was used with maximum output power of 6 kW. The laser-metal interaction zone was shielded by an argon flow. Sample thicknesses varied between 1 and 3 mm and travel speeds ranged from 6 m/min to 11 m/min, according to the sheet thickness and the laser power. The plasma optical emission was collected by a quartz collimator and transmitted to the optical sensor by a 50 μm core-diameter optical fiber. Spectral lines from three different chemical species (Mn(I), Fe(I), Cr(I)) composing the plasma plume and the stainless steel alloy were used for the acquisition of the electron temperature and the correlation signals [1]. The minimum acquisition time for each spectrum, necessary for the calculation of each electron temperature point, was 3 ms. The defect detection algorithm consisted in comparing the electron temperature of the welding process under examination with a reference baseline and two adjustable error thresholds. The reference signal was computed during a self-learning procedure in which preliminary sound welds were carried out. The upper and lower error thresholds were defined by adding or subtracting an adjustable fraction of the average standard deviation of the sample signals, according to the desired sensitivity of the monitoring system. The temporal evolution of the electron temperature of the plasma plume and of the correlation coefficient have been monitored simultaneously during the process. For the purpose of the covariance analysis, we computed a sliding window of N=10 consecutive spectra, each time. Together with the process speed, the number N determines the maximum achievable spatial resolution of the correlation signals. The number N also influences the value of m_{ij} corresponding to the confidence level of 95% which was selected as the threshold for the joint quality evaluation procedure.

4. Results and discussion

Figure 1 shows a typical plasma emission spectrum acquired during the laser welding process of the industrial production line of stainless steel pipes that we have chosen as case study for the test of our sensor. The emission lines selected for the correlation analysis are evidenced in the picture.

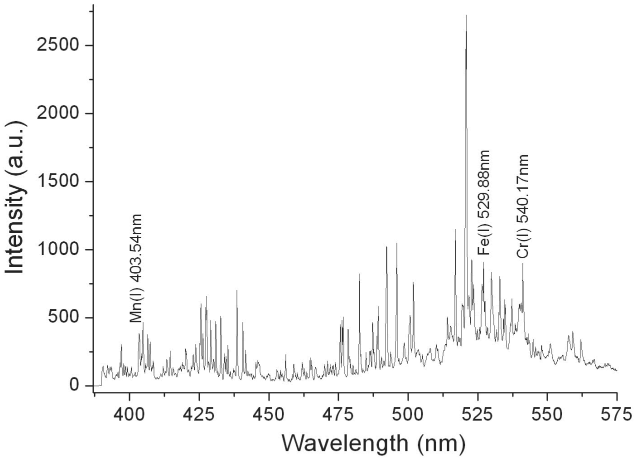

Fig. 1. Visible spectrum of the plasma optical emission during a CO_2 laser welding process of stainless steel pipes

Figure 2 shows the response of the sensor for a 3-m long segment of defect-free welded joint. It is clearly evident that the acquired electron temperature signal was quite steady, standing between the two threshold lines. Also the correlation signal between the Mn(I) and Cr(I) emission lines is, for all the sampled joint length, well above the confidence level threshold. Both visual inspections and X-ray analyses of the corresponding butt-welded pipe confirmed the absence of defects.

Once we calibrated the sensor along with the optimized welding parameters, a series of unacceptable welds were intentionally produced by varying the main process parameters. Correspondingly, the temperature and correlation signals versus the position on the welded joint were acquired. Thus, the sensitivity of the defect detection algorithm was evaluated when some defects occurred. Figure 3 illustrates the case in which the welding speed and the gas flow rate were fixed and a lower incident power caused a lack of weld penetration. Consequently, instabilities in the molten pool and in the plasma plume were induced that have been detected by the sensor as an out-of-threshold excursion of the electron temperature signal and two evident drops of the correlation signals, below the confidence level. In this case two couples of lines were examined for the correlation analysis. Both signals exhibited analogous behavior.

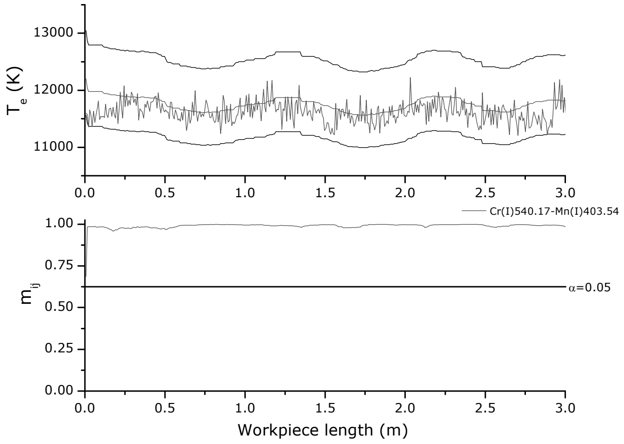

Fig. 2. Cr(I) electron temperature and correlation signals for a laser welded pipe without defects. α factor indicates the chosen confidence level for correlation analysis

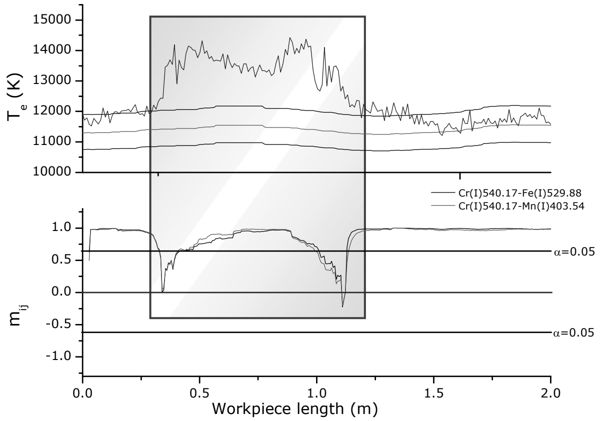

Fig. 3. Cr(I) electron temperature and correlation signals for variable laser power

For linear heat inputs lower than the optimal value defined for each workpiece thickness, the shape of the welded seams are irregular and affected by defective profiles. In this particular experimental condition a partial penetration regime is established due to the lower incident laser power. In our case the lack of penetration was confirmed by post-process X-ray and radial strength analyses on the welded pipe.

The linear energy input to the material may be also altered by changing the welding speed. Figure 4 shows results obtained by temporarily increasing the welding speed in two localized segments of the welded joint. For excessively fast travel speeds the heat input on the metal surface is too low to sustain the keyhole, causing a partial penetration of the workpiece. Post-process analyses of the welded joints cross-sections showed, in fact, that the keyhole shape was shallow and broad. In such process conditions the beam absorption deep inside the metal was less efficient, the keyhole was unstable and, as a consequence, the plasma electron temperature suddenly changed. In addition, the balances among the chemical species inside the plume have been strongly affected by this plasma instability, thus causing two drops of the correlation signals. The experimental results have supported our hypothesis that the spectroscopic signals coming from the plasma plume are very responsive to any change in the process parameters leading to weld defects.

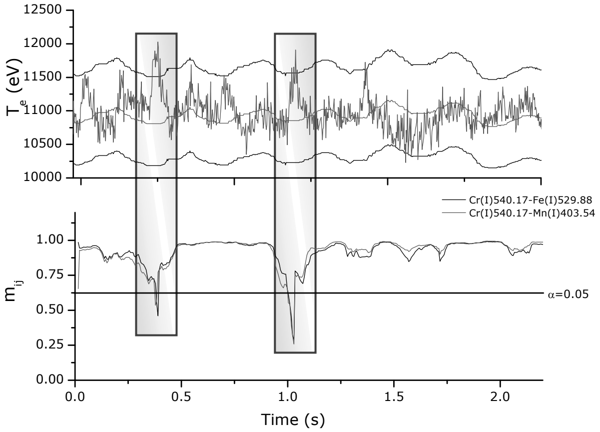

Fig. 4. Cr(I) electron temperature and correlation signals for variable welding speed

One of the further advantages of our optical sensor is that electron temperature and correlation signals allow any operator to optimize the values of the main process parameters, like welding speed or laser power, in order to obtain welded pipes without defects.

5. Summary and conclusions

A spectroscopic sensor prototype for real-time laser welding process monitoring has been developed. It is based on the acquisition of the optical spectra emitted from the laser generated plasma plume and implements on-line algorithms for the calculations of the plasma electron temperature and the analysis of correlation between selected spectral lines. Experimental results have been shown of a field application of the optical sensor in a real industrial production line of laser-welded stainless steel tubes. The sensor has been demonstrated to discriminate sound welds from defective joints caused by a wrong combination of process parameters, e.g. laser power and welding speed.

Compared to other optical sensors, the main advantage of this system is that it has a great flexibility upon variation of the welding metal or the joint geometries. In fact once the chemical composition of the alloy was known and most plasma emission lines are identified, only a slight calibration of the software settings is necessary.

A patented commercial version of this sensor (TRWOC from T.E.R.N.I. Research) is already available on the market.

The capability of identifying the cause of the defect, once it has been detected is still limited to specific cases. Future work will regard the “intelligent” fusion of various sensor technologies aiming to increase the reliability of the system and, hopefully, realize a flexible and robust closed-loop control of the laser welding process.

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