Spectroscopic analysis technique for arc-welding process control

Jesús Mirapeix*, Adolfo Cobo, Olga Conde, María Ángeles Quintela, José-Miguel López-Higuera
Grupo de Ingeniería Fotónica; Dept. T.E.I.S.A.
Universidad de Cantabria, Avda.Los Castros s/n, 39005 Santander, Spain

ABSTRACT

The spectroscopic analysis of the light emitted by thermal plasmas has found many applications, from chemical analysis to monitoring and control of industrial processes. Particularly, it has been demonstrated that the analysis of the thermal plasma generated during arc or laser welding can supply information about the process and, thus, about the quality of the weld. In some critical applications (e.g. the aerospace sector), an early, real-time detection of defects in the weld seam (oxidation, porosity, lack of penetration, ...) is highly desirable as it can reduce expensive non-destructive testing (NDT). Among others techniques, full spectroscopic analysis of the plasma emission is known to offer rich information about the process itself, but it is also very demanding in terms of real-time implementations.

In this paper, we proposed a technique for the analysis of the plasma emission spectrum that is able to detect, in real-time, changes in the process parameters that could lead to the formation of defects in the weld seam. It is based on the estimation of the electronic temperature of the plasma through the analysis of the emission peaks from multiple atomic species. Unlike traditional techniques, which usually involve peak fitting to Voigt functions using the Levenberg-Marquardt recursive method, we employ the LPO (Linear Phase Operator) sub-pixel algorithm to accurately estimate the central wavelength of the peaks (allowing an automatic identification of each atomic species) and cubic-spline interpolation of the noisy data to obtain the intensity and width of the peaks.

Experimental tests on TIG-welding using fiber-optic capture of light and a low-cost CCD-based spectrometer, show that some typical defects can be easily detected and identified with this technique, whose typical processing time for multiple peak analysis is less than 20msec. running in a conventional PC.

Keywords: spectroscopy, plasma emission, arc-welding, real-time processing.

1. INTRODUCTION

Several different approaches have been proposed for the analysis of welding processes, from the measurement of the charge voltage induced by the plasma on the welding nozzle [1], to acoustic emissions [2] or imaging in different spectral bands. It has been demonstrated that, by means of spectroscopic analysis of the plasma generated during the welding process, a relationship between some plasma parameters (typically the electronic temperate and density of the plasma) and the resulting quality of the weld seam can be established [3].

For those parameters to be obtained from the plasma spectrum, a precise analysis of the emission peaks from the various species contributing to the plasma must be carried out, involving central peak wavelength, amplitude and peak width. Some solutions have been developed by using iterative techniques to perform a peak fitting to previously established known functions, but these strategies are specially time consuming. For a proper design of a real sensor system, that should be able not only to detect defects but to actuate over the process to assure an optimal result, real-time operation is required.

A new real-time technique being able to process the spectrum obtained from the plasma plume, to identify the spectral lines within the range of interest and finally to detect even small discontinuities in the weld seam for arc welding processes is presented in this paper. The LPO sub-pixel operator [4] will be demonstrated to be an optimal solution for the central peak wavelength determination problem.

*mirapeixjm@unican.es; Phone: +34-942-200877 ext.15; Fax: +34-942-200877; http://grupos.unican.es/gif/

Photonics Applications in Industry and Research IV, edited by Ryszard S. Romaniuk, Stefan Simrock, Vladimir M. Lutkovski,
Proc. of SPIE Vol. 5948, 594824, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.621939

2. PEAK WAVELENGTH AND INTENSITY ESTIMATION

As there exist a large amount of different emission lines which can be identified within just 1nm, the process of precisely identifying the atomic species attached to every spectral line is specially difficult. Besides, there is another constraint regarding this process: the low resolution achievable with low-cost CCD spectrometers (being this resolution directly related to the product of the pixel width with the linear dispersion of the spectrometer's grating at the detector plane). These difficulties can be overcome when the bandwith of the peak being analyzed exceeds one single pixel by using the so-called sub-pixel algorithms. These algorithms are commonly used for the improvement in the detection accuracy of FBG sensors [4-5], using the registered information of the signal over several adjacent pixels in order to establish more precisely the central peak position.

One of the most widely used sub-pixel algorithms is the Centroid Detection Algorithm (CDA), which is based in the calculation of the "mass-center" of the peak:

$$\lambda_{sub} = \frac{\sum_j \lambda_j i_j}{\sum_j i_j}, \tag{1}$$

Where λ_{sub} is the peak center wavelength, and i_j and λ_j the intensity and wavelength associated to the jth pixel.

When assuming that the peak being analyzed fits a Gaussian profile, another sub-pixel method based on a Gaussian approximation can be used:

$$\lambda_{sub} = \lambda_0 + \frac{1}{2}\left(\frac{\ln(R(\lambda_0 - 1)) - \ln(R(\lambda_0 + 1))}{\ln(R(\lambda_0 - 1)) - 2\ln(R(\lambda_0)) + \ln(R(\lambda_0 + 1))}\right), \tag{2}$$

whit λ_{sub} the new sub-pixel estimation, λ_0 is the (integer) pixel number at the peak maximum and R the intensity of the spectrum.

In this paper, a sub-pixel algorithm designed for the enhancement of the detection accuracy of FBGs sensors (LPO: linear phase operator technique [4]) is implemented in the proposed system in order to improve the resolution in the central peak position determination, allowing a more precise spectral-line identification. The LPO operator combines a finite impulse response (FIR) transfer function with a linear interpolation step. Having selected a fourth-order LPO operator as the most suitable for our process, the subpixel location λ_{sub} of a FBG spectrum will be:

$$\lambda_{sub} = \lambda_0 + \frac{g(R,\lambda_0)}{g(R,\lambda_0) - \xi(R,\lambda_0 + 1)} \; for \; R(\lambda_0 - 1) < R(\lambda_0 + 1), \tag{3}$$

Where λ_0 the (integer) pixel location at the maximum, R the recorded intensity of the spectrum and

$$\begin{aligned} g(R,\lambda_0) &= -R(\lambda_0 - 2) - R(\lambda_0 - 1) + R(\lambda_0 + 1) + R(\lambda_0 + 2) \\ \xi(R,\lambda_0 + 1) &= -R(\lambda_0 - 1) - R(\lambda_0) + R(\lambda_0 + 2) - R(\lambda_0 + 3) \end{aligned} \tag{4}$$

It is worth noting that, although some other techniques concerning peak-fitting are also possible for the central peak position estimation, the restrictions imposed by the real-time assumption suggest the utilization of computationally efficient algorithms such as the LPO.

Once the central wavelength has been estimated, the specific emission line is identified by using a local copy of the NIST atomic spectra database [6] with a hash-based search algorithm. The intensity corresponding to the estimated central wavelength is obtained with a cubic-spline interpolator. This algorithm is more efficient than classical recursive peak fitting techniques (e.g. Levenberg-Marquardt [7]).

3. SUB-PIXEL ALGORITHMS COMPARISON

The three different sub-pixel algorithms detailed in section three have been implemented in order to compare their performance within the proposed arc welding analysis system. Some particular tests were carried out to check both their respective processing times (parameter of main importance as a real-time system is being considered) and their ability to precisely identify the various spectral lines appearing in our processes. In the Table 1 a comparison between the processing times of the sub-pixel algorithms is presented.

Table 1. Sub-pixel algorithms

Weld time (sg)	Number of spectra	Number of peaks	Processing time (msg)	No Sub-pixel	LPO	CDA	Gaussian Fit
8	401	35.38	Total	5878	6102	6146	6140
8	401	35.38	Sub-pixel	301	492	500	522
8	306	55.01	Total	4742	4929	4915	4963
8	306	55.01	Sub-pixel	271	459	463	509

In Table 1, the tests considered involved all the possible pair of spectral lines for a given chemical species (in this case Ar II), which are afterwards taking into account for the T_e calculation process. This kind of test has been considered because it implies the utilization of several different spectral lines, allowing a better discrimination among the performances of the sub-pixel algorithms. The number of spectra is the amount of single spectra which were recorded and thus processed for each weld test, while the number of peaks is the mean number of the peaks which enter the sub-pixel routine during the whole process. Two different processing times are also included in the table, the total processing time (from the capture of the spectra to the electronic temperature calculation) and the sub-pixel processing times, considering in this case not only the sub-pixel processing time, but also the one spent by the cubic-spline interpolator. It can be seen that LPO is the sub-pixel operator that presents best sub-pixel times, although they tend to be next to those exhibit when using CDA. However, the Gaussian-fit operator is always slower than the others in any circumstance.

Another analysis was performed to compare the performance of the sub-pixel algorithms. During the process, the difference between the central wavelength of each processed peak (obtained directly from the spectrometer without sub-pixel processing), and the expected wavelengths from the NIST database, as well as the difference between the resulting sub-pixel wavelength and the NIST ones were determined. In Table 2 the results for three intense spectral lines corresponding to Ar I (416 nm), Fe I (420 nm) and Cr I (435 nm) are presented.

Table 2. Comparison of sub-pixel algorithms: emission line identification accuracy

Wavelength difference	LPO	Gaussian-fit	CDA
$\lambda_{CCD} - \lambda_{NIST}$ (pm)	72.85	96.37	94.56
$\lambda_{SUB-PIXEL} - \lambda_{NIST}$ (pm)	41.27	57.77	63.94

It can be noted that LPO exhibits the lowest differences for the two calculations, suggesting that it is the best among the three. However, this test is not conclusive, and although in most of the cases that affirmation is true, there exist some cases in which CDA obtains better results. Nonetheless, we consider that the previous calculations are merely a hint of the performance of the algorithms, as in many cases its consideration implies a different identification of a particular peak. All in all, we estimate that the LPO operator is the best for our specifications, and that it is the one which identifies more properly the selected spectral lines.

The algorithms previously detailed have been implemented with C#, and integrated within a complete arc welding system in order to be tested and validated. The experimental setup is described in the next section.

4. EXPERIMENTAL SETUP AND RESULTS

The system designed to check the validity of the developed technique is schematically described in figure 1. To perform TIG welds, the "Kemppi Mastertig 2200" power source was selected (with an output intensity ranging from 5 to 220 A). While the torch in our system was fixed, the plates used for the tests were controlled by a high-precision positioning system, formed by the controller (Newport MM4005) and two linear stages (Newport MTM100PP1), with a resolution of 1μm in both axes. The end of the tungsten rod electrode (1mm diameter) was placed at 2 mm from the plates. In our experiments only AISI-304 stainless steel plates were used, although the material to be welded does not imposed any restriction in the proposed system.

The optical instrumentation of the system was formed by a collimating lens receiving the light emitted from the plasma and a solarization resistant optical fiber (Ocean Optics P400-UV-SR) used to guide the light from the collimator to the spectrometer. This low-cost, 2048 linear CCD spectrometer, (Ocean Optics USB2000), has a spectral resolution of 0.3 nm and spectral range from 195 to 535 nm. Argon was used as shielding gas, with a typical flow rate of 12 L/min.

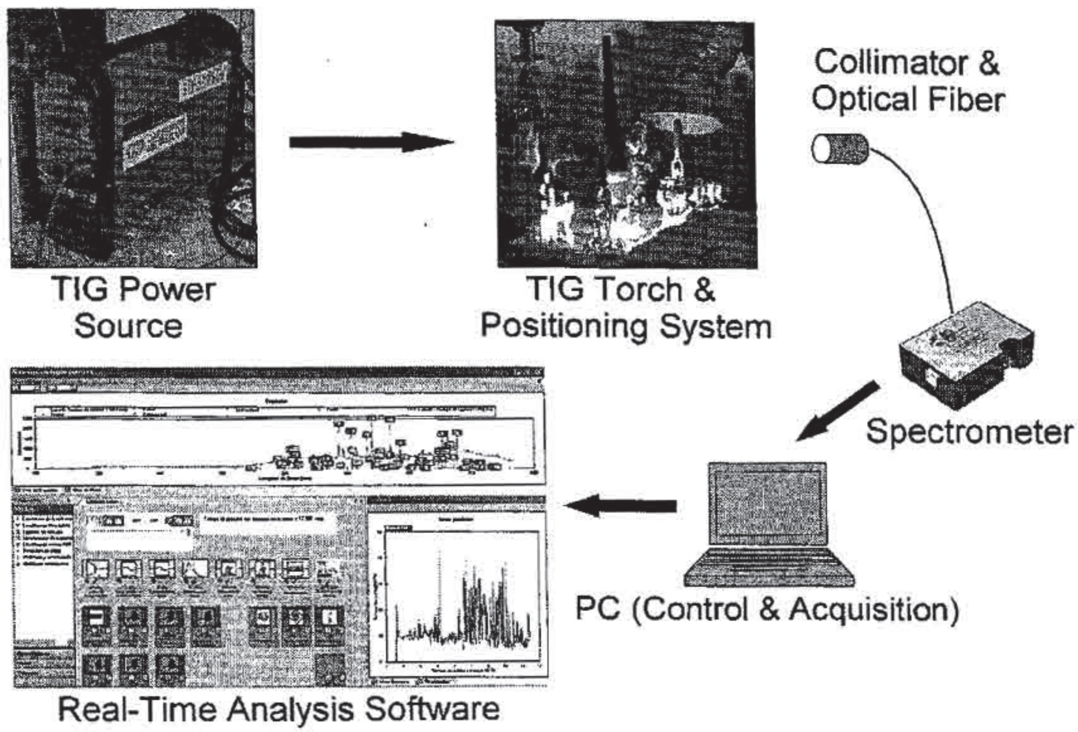
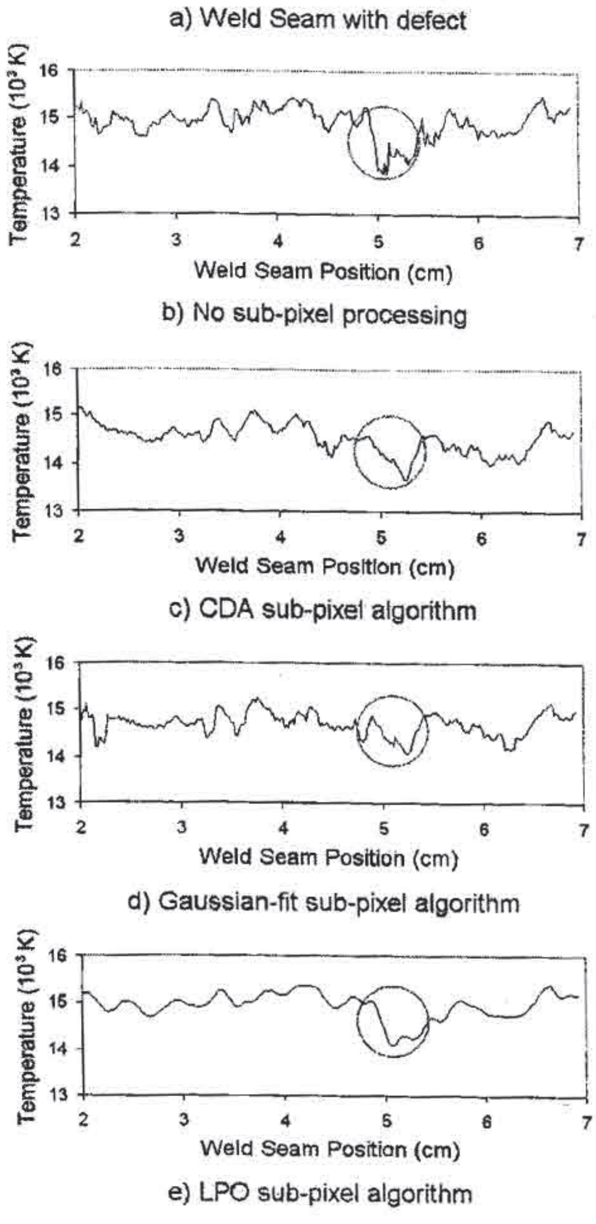


Figure 1. Experimental setup.

Various experiments were performed by varying both the intensity and the flux of shielding gas during the welding process, producing in some cases visible defects in the weld seam. In figure 2 a weld seam with a small defect is presented. This defect was caused by a reduction in the gas flux from 12 L/min to 6 L/min. In figure 2 (a), where the bottom of the weld seam is shown, the defect is located at $x \approx 5$ cm, Figures 2(b), (b), (d) and (e) present the results of including during the analysis process: (b) no sub-pixel processing, (c) CDA sub-pixel algorithm, (d) Gaussian-fit sub-pixel algorithm and (e) LPO sub-pixel operator.



-Figure 2. Comparison of sub-pixel algorithms in weld defect identification

When no sub-pixel algorithm is included, the resulting T_e (calculated with Ar II emission lines) is clearly noisier, as the central peak wavelength obtained from the spectrometer is more difficult to be attached to a single spectral line during the whole process. However, when using LPO, T_e is less noisy, involving that the detection of events along the weld seam is obviously easier. Figures 2(c) and 2(d) show that the mean value of T_e when using CDA and Gaussian-fit is not as stable as in the LPO case, which obscures the defect detection at x=5cm.

5. CONCLUSIONS

A new system based on plasma spectroscopy aimed at the real-time detection of defects in arc weld seams has been proposed. The main novelty of this system is the introduction of a sub-pixel algorithm, the LPO, in order to allow a fast and precise identification of the spectral lines found in our spectra. Our experiments have demonstrated, not only that with LPO real-time operability is feasible, but also that this sub-pixel operator is better in comparison to others as it reduces some instabilities in the electronic temperature T_e calculation process. Detection of small defects has been presented, showing the benefits of the selection of the LPO operator as the central wavelength estimator, as it allows a clearer recognition of the above-mentioned weld-seam defects. Further works for a real-time implementation of the Boltzmann technique in the proposed system are currently being developed.

ACKNOWLEDGEMENTS

Authors thank the Spanish Government under the Ministry of Science and Technology for its support through the EOAMOP (TIC'2002-01259) R&D project.

REFERENCES

1. L. Li, D. J. Brookfield, W M. Steen, "Plasma charge sensor for in-process, non-contact monitoring of the laser welding process", Meas. Sci. Tech. v 7, n 4, 1996, pp. 615-626.
2. H. P. Gu, W. W. Duley, "Resonant acoustic emission during laser welding of metals", Journal of Physics D- Applied Physics, 29 (3) 1996, pp. 550-555.
3. Antonio Ancona, Vincenzo Spagnolo, Pietro Mario Lugara, Michelle Ferrara, "Optical sensor for real-time monitoring of CO_2 laser welding process", Applied Optics, 40 (33) 2001, pp. 6019-6025.
4. Thomas Zeh, Hans Schweizer, Andreas Meixner, Andreas Purde, Alexander W. Koch, "Enhancement of detection accuracyof fiber Bragg grating sensors", Proceedings of SPIE, V 5502 (2004), pp. 540-543.
5. A. Ezbiri, S.E. Kanellopoulos, V.A. Handerek, "High resolution instrumentation system for fibre-Bragg grating aerospace sensors", Optics Communications, 150 (1998), pp. 43-48.
6. NIST atomic spectra database (http://physics.nist.gov/cgi-bin/AtData/main_asd).
7. A.W. Robinson, P. Gardner, A.P.J. Stampfl, R. Martin, G. Nyberg, "Error analysis in the fitting of photoemission lineshapes using the Levenberg-Marquardt method", Journal of Electron Spectroscopy and Related Phenomena, v 94, n 1-2, 1998, pp. 97-105.