Estimation of the plasma spectrum RMS signal as an alternative spectroscopic approach for arc-welding quality monitoring

Adolfo COBO, Jesús MIRAPEIX, Pilar B. GARCIA-ALLENDE, José J. VALDIANDE, José-Miguel LOPEZ-HIGUERA

1. Grupo de Ingeniería Fotónica, Edificio I+D Telecomunicaciones, Universidad de Cantabria, Av. Los Castros s/n, 39005, Santander.

Contact name: Adolfo COBO (adolfo.cobo@unican.es).

ABSTRACT:

Plasma spectroscopy has demonstrated its potential within the framework of welding process quality monitoring. The analysis of the welding plasma spectrum, which is formed by several emission lines from the different elements participating in the process, gives rise to spectroscopic parameters exhibiting a direct correlation to the quality of the resulting seams. The plasma electronic temperature has been the traditional selection in this regard, mainly by using an approximation where only two emission lines from the same species are involved in the calculations. However, for a completely automated system, the computational cost involved in the process could be a serious drawback. In this paper we propose the use of the plasma spectrum RMS (Root Mean Square) signal as an alternative spectroscopic approach, as it will be demonstrated that this parameter can be also used to identify the appearance of weld defects in an on-line quality monitoring system.

Key words: plasma spectroscopy, arc-welding, optical fiber, quality monitoring

1.- Introduction

Welding processes, mainly arc and laser, are nowadays involved in different key industrial areas, like aeronautics or the fabrication of cars and heavy components for nuclear power stations, just to mention some examples where quality requirements are very demanding. Obviously, in these frameworks the appearance of a weld flaw could be catastrophic, what makes it necessary to spend a lot of effort and time in analyzing each particular welding process and material involved in advance to determine the optimal input welding parameters that will minimize the occurrence of weld flaws. In addition, non-destructive techniques (NDT) must also be employed, once the process has finished, to verify that the seam is free of defects, and that the specific quality requirements are fulfilled. In this context, where the complexity of the physics involved has made it difficult to obtain an effective model relating the process input parameters to the output seam quality [1,2], the availability of a reliable on-line monitoring system would be a great asset. However, in spite of the great research effort developed in this field [3,4,5,6], the industry is still reluctant to use these system for production, especially if a system feedback is considered.

In the last years, several companies have started to show interest for this kind of solution, and plasma spectroscopy is well placed among the different approaches. The correlation between the plasma electronic temperature and the seam quality is weld known [6,7,8]. In addition, new research lines within this field have been proposed [9,10], and tests on real industrial applications can be also found [11], what demonstrates the validity of this solution.

Recently, new implementations focused on the reduction of the computational cost have been proposed [12]. It is worth noting that this parameter is directly related to the spatial resolution of weld defects of the system, and it is of special relevance for laser applications, where the welding speed is much higher than in arc-welding scenarios. In a previous contribution we proposed a new spectroscopic approach based on the estimation of the wavelength associated with the maximum intensity of the plasma continuum [12]. In this paper we proposed the use of the plasma spectrum RMS (Root Mean Square) signal for monitoring purposes. A similar approach was explored by Wang et al. for laser welding of titanium alloys by using a photodiode [13]. We will demonstrate the feasibility of our proposal by showing the correlation of the plasma RMS profiles to the seam quality events using a CCD-spectrometer to collect the welding plasma spectra.

2.- Plasma diagnostics

The RMS signal of the plasma spectrum is calculated by considering the intensity provided by each pixel of the CCD spectrometer considered in the setup

$$S_{RMS} = \sqrt{\frac{1}{n}\sum_{i=0}^{n-1} x_i^2}\ , \qquad (1)$$

where n is the total number of pixels of the CCD and x_i the intensity corresponding to the i-th pixel. This signal is a measurement of the plasma spectrum energy within the spectral range considered, and it is also related to the total arc power, and consequently to the process heat input.

The most common spectroscopic parameter chosen for monitoring purposes, the plasma electronic temperature T_e, can be determined by means of the Boltzmann-plot, which is derived from the Boltzmann equation [14]

$$\ln\left(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}\right) = \ln\left(\frac{hcN}{Z}\right) - \frac{E_m}{kT_e}\ , \qquad (1)$$

where E_m is the upper level energy, g_m the statistical weight, A the transition probability, λ the wavelength, I the emission line relative intensity, k the Boltzmann constant, h the Planck's constant, c the light velocity, N the population density of the state m and Z the partition function. The representation of the left-hand side of Eq. (1) versus E_m has a slope inversely proportional to T_e. This expression can be simplified by choosing only two lines and using Eq. (2)

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

Eq. (2) is commonly employed for on-line welding monitoring, given its reduced computational cost. However, it is worth noting that the temperature profiles will be noisier with this approach, what can be a problem for this kind of application.

In terms of the computational cost of both alternatives, it should be mentioned that several processing stages can be removed of the system when the plasma RMS signal is chosen as the monitoring parameter. This can be observed in the schematic representation depicted in Fig. 1, where all the processing steps necessary to obtain T_e have been indicated. It can be appreciated that four additional stages are required, being the one labeled as "Line identification" the most relevant in terms of computational cost. It has been already mentioned that, to obtain an estimation of T_e, the emission lines appearing in the plasma spectra have to be identified, i.e. associated with its corresponding species (element and ionization stage). This process is especially time consuming, as a search in a local database has to be performed, and this database should contain all the spectroscopic information of all the possible emission lines to be found within the spectral range considered.

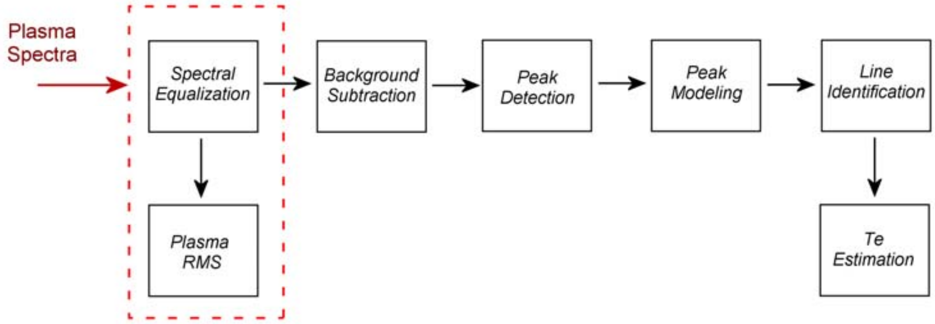

Fig.1: Processing stages required to obtain T_e and Plasma-RMS

3. Experimental issues and results

Several experimental tests have been carried out to check the validity of the proposed approach. To extend the application field we will present tests performed on stainless-steel (AISI-304) and INCONEL 690. The former were carried out in the laboratory, using a conventional TIG (Tungsten Inert Gas) welding setup formed by a TIG power source (Kemppi Mastertig 2200) and a TIG torch (Kemmpi TTC 220). The plasma radiation was collected by an optical fiber of 50 µm core diameter attached to a CCD-spectrometer.

In the experiment shown in Fig. 2, an inclusion of aluminium was placed on the plate, approximately in the middle of the resulting seam. The purpose was to elucidate whether the system was able to identify the appearance of external materials within the welding process. Obviously, it is expected that the mentioned inclusion will give rise to some perturbation within the process, being this perturbation translated to the welding plasma. In the plasma RMS profile depicted in Fig. 2(a) a clear perturbation can be observed associated with the Al inclusion. Fig. 2(b) shows the difference between the spectrum associated with the correct welding, which was performed with a constant welding current of 50 A and the one corresponding to the presence of Al in the plasma.

Another experimental test was designed to verify the response of the plasma RMS signal according to welding current variations. The experimental setup was the same as in the previous test, but the CCD spectrometer used was different, being in this case an Ocean Optics USB2000 with 2048 pixels and a spectral range from 195 to 535 nm, also used in the field tests presented in Fig. 4, and in the previous one an Ocean Optics HR4000 with 3648 pixels and a spectral range from 370 to 500 nm approximately. The resulting seam and its associated plasma RMS profile are depicted in Fig.3. It can be observed that the RMS signal exhibits a clear correlation with the welding current variations (37 and 42 A) also indicated in Fig. 3(b).

Fig. 4 presents the results obtained on a field test in the facilities of ENSA (Equipos Nucleares S.A.) in Maliaño, Spain. ENSA is a company devoted to the fabrication of heavy components mainly for the nuclear sector. The process under analysis was the orbital TIG-welding of an INCONEL 690 tube in a welding coupon. Details regarding this particular process can be consulted in [11]. In fact, Fig. 9 of that reference contains an analysis of the seam presented in Fig. 4 by means of the so-called traditional spectroscopic approach, i.e. with a T_e profile. By comparing Fig. 4(a) and (b), it can be appreciated how the defective section of the tube seam, that was created by the operator by blowing over the welding zone (simulating in this way a perturbation on the shielding gas), is associated with strong perturbations in the RMS profile, what would allow to identify that defect in an on-line process.

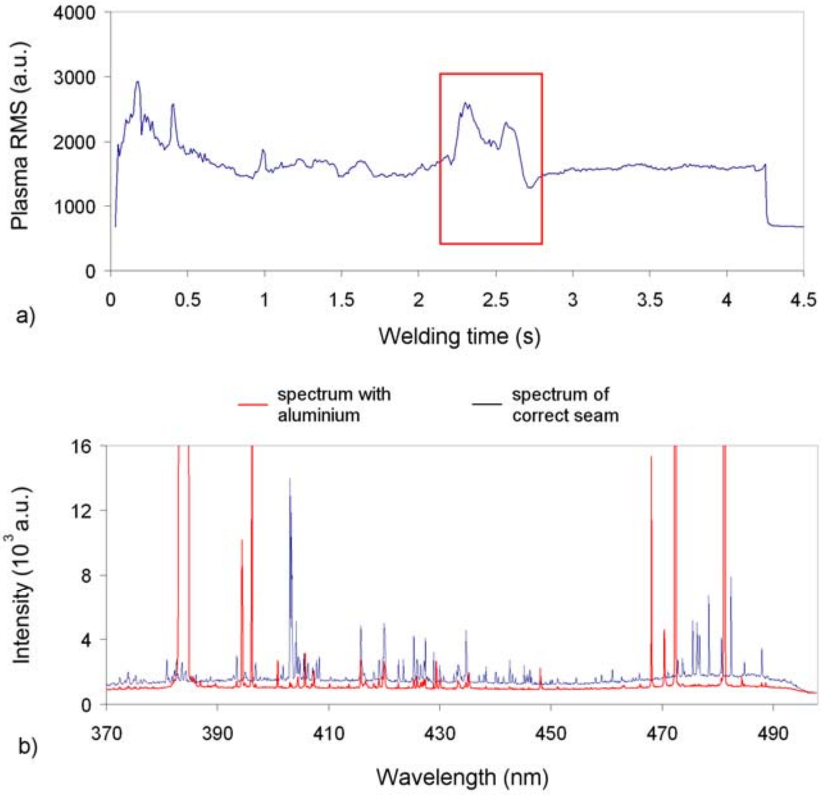

Fig.2: Plasma-RMS profile and spectra of seam with aluminium

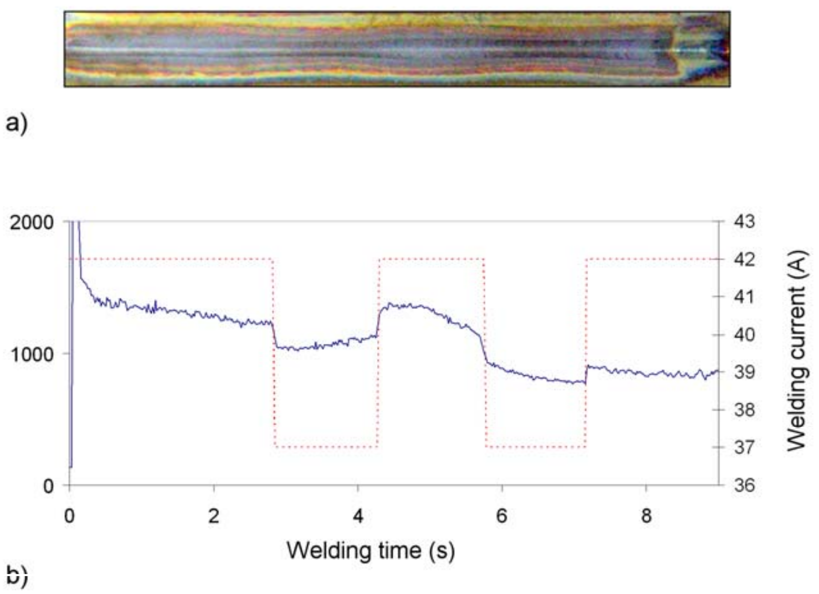

Fig.3: Plasma-RMS profile for seam with different welding currents.

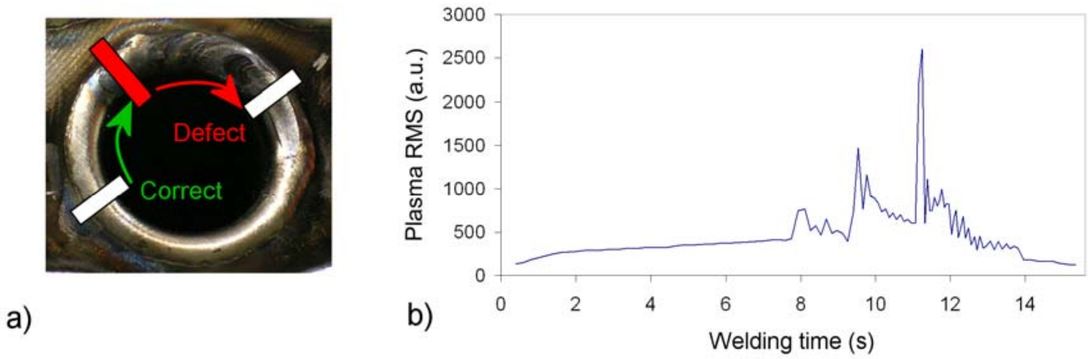

Fig.4: Plasma-RMS for orbital tube-to-tubesheet defective seam

4.- Conclusion

A new spectroscopic approach for on-line welding quality monitoring has been presented in this paper. This solution is based on the estimation of the RMS signal of the welding plasma spectra acquired by means of a CCD-spectrometer. Several tests performed on both AISI-304 stainless-steel and INCONEL 690 have proved the correlation between the appearance of defects in the seam and the associated plasma RMS profiles. It is worth noting that the tests on INCONEL 690 correspond to field tests of a tube-to-tubesheet orbital welding process, what suggests the applicability of this approach in real industrial scenarios. Its main advantage is its reduced computational cost compared to the traditional spectroscopic approach based on the determination of the plasma electronic temperature. In this case, an identification of the plasma emission lines has to be fulfilled, what implies a significant computational cost. The reduction of the computational time per sample allows to improve the spatial resolution of the system, what is always interesting, but of special relevance in laser welding processes, where this technique could be also applied. Further studies regarding field tests on different samples, and a more detailed analysis of possible defects will be conducted.

Acknowledgements: This work has been co-supported by the project TEC2007-67987-C02-01. Authors also want to thank the staff from ENSA, specially F. Linares and D. Solana, for their valuable help and support during the field tests.

References

[1] T.W. EAGAR, "*Physics of arc welding processes*", in Proc Int Inst Weld Congr, vol. 61, 1990.

[2] C. S. WU, M. USHIO, M. TANAKA, "*Analysis of the TIG welding arc behaviour*", Computat Mater Sci, vol. 7, pp. 308-314, 1997.

[3] L. LI, D.J. BROOKFIELD, W.M. STEEN, "*Plasma charge sensor for in-process, non-contact monitoring of the laser welding process*", Measurement Science & Technology, vol. 7, pp. 615-26, 1996.

[4] H. GU, W.W. DULEY, "*Statistical approach to acoustic monitoring of laser welding*", J Phys D, vol. 29, pp. 556-60, 1996.

[5] R. KOVACEVIC, Y.M. ZHANG, S. RUAN, "*Sensing and control of weld pool geometry for automated GTA welding*", Journal of Engineering for Industry, Transactions of the ASME, vol. 117, pp. 210-22, 1995.

[6] P. SFORZA, D. DE BLASIIS, "*On-line optical monitoring system for arc welding*" NDT E. Int., vol. 35, pp. 37–43, 2002.

[7] A. ANCONA, V. SPAGNOLO, P.M. LUGARA, M. FERRARA, "*Optical sensor for real-time monitoring of CO2 laser*

welding process", Appl. Opt., vol. 40, pp. 6019-25, 2001.

[8] J. MIRAPEIX, A. COBO, C. JAUREGUI, J.M. LOPEZ-HIGUERA, "*Fast algorithm for spectral processing with application to on-line welding quality assurance*", Meas. Sci. Technol., vol. 17, pp. 2623-2629, 2006.

[9] T. SIBILLANO, A. ANCONA, V. BERARDI, E. SCHINGARO, P. PARENTE, P.M. LUGARA, "*Correlation spectroscopy as a tool for detecting losses of ligand elements in laser welding of aluminium alloys*", Opt Lasers Eng, vol. 44, pp. 1324-35, 2006.

[10] J. MIRAPEIX, A. COBO, D.A. GONZÁLEZ, J.M. LOPEZ-HIGUERA, "*Plasma spectroscopy analysis technique based on optimization algorithms and spectral synthesis*", Opt. Express, vol. 15, pp. 1884-97, 2007.

[11] A. COBO, J. MIRAPEIX, F. LINARES, J.A. PINEY, D. SOLANA, J.M. LOPEZ-HIGUERA, "*Spectroscopic Sensor System for Quality Assurance of the Tube-To-Tubesheet Welding Process in Nuclear Steam Generators*", IEEE Sensors J., vol. 7, pp. 1219-24, 2007.

[12] J. MIRAPEIX, A. COBO, S. FERNANDEZ, R. CARDOSO, J.M. LOPEZ-HIGUERA, "Spectroscopic analysis of the plasma continuum radiation for on-line arc-welding defect detection", J Phys D, vol. 41, pp. 135202-10, 2008.

[13] C. WANG, L. HU, X. HU, J. LIU, "*Relationship between plasma optic signal and penetration depth for partial-penetration laser welding*" Chin J Mech Eng Engl Ed, vol. 19, pp. 109-12, 2006.

[14] H.R. GRIEM, *Principles of Plasma Spectroscopy*, (Cambridge University Press, 1997).