Spectroscopic Optical Sensors for Welding Diagnostics

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***Abstract* – A review of solutions involving plasma optical spectroscopy applied to on-line welding quality monitoring is presented in this paper. After a brief introduction to welding processes and their requirements in terms of quality monitoring, different proposals for on-line monitoring will be addressed. The basics of welding monitoring via plasma spectroscopy in terms of light capture and hardware and processing requirements will be also introduced, and different approaches will be presented. Finally, a variety of examples regarding field trials in different sectors will be also discussed.**

I. INTRODUCTION

Welding plays a major role in a wide variety of industrial scenarios, with relevant examples in the energy sector (pipelines, wind turbines, nuclear generators, among others), aeronautics, the automotive industry or in civil engineering, just to mention some relevant examples. Although there are many different welding processes, from electron beam welding to friction stir welding; arc and laser welding are two of the more significant and popular varieties. The complexity of the physics involved is common to all these cases, and a good example lies in arc-welding processes, where temperature differences of several thousand Kelvins can be found in very reduced areas, the materials involved can be found in solid, lyquid, gas or plasma states, transport and radiative mechanisms have to be considered and several input parameters like the welding current, the cut-off distance, the protection gas selected and its flow rate, the temperature and humidity of the environment and some others may affect the final result.

Within this framework, some industrial scenarios exhibit demanding requirements in terms of the resulting quality of the seams. However, the complexity inherent to the process mentioned above has made it difficult to obtain theoretical models able to offer a suitable performance in terms of process design [1]. In this regard, the typical procedure in the industry involves the use of time-consuming procedure trials and welding coupons to establish the optimal input parameters minimizing the appearance of welding flaws. Once the seam has been performed, non-destructive testing (NDT) techniques are employed at different process stages to determine if the welds satisfy a specific quality standard. Examples of these techniques are X-rays, ultrasonic or Eddy current testing, magnetic particles and so on [2], also including visual inspection.

Although these techniques are important and can not be avoided, the potential benefits of an efficient on-line monitoring system have given rise to an intense research in this area during the last years. The final goal of this kind of systems would be, not only to allow a real-time detection of the appearance of a defect, thus allowing an in-situ repair when possible, but also to correct some parameters during the process in an attempt to prevent or reduce the negative effects of those flaws. It seems clear that a reliable on-line monitoring system might allow to improve the productivity and to better understand the process under analysis

II. ON-LINE WELDING MONITORING

A. Non-spectroscopic approaches

There are different solutions that have dealt with on-line monitoring of welding processes, particularly of the arc and laser varieties. A typical approach lies in the employment of solutions that allow an estimation of the electrical signals of the process [3]. Capacitive sensing between the welding nozzle and the workpiece has also been proposed [4] for laser welding processes. There are also proposals based on machine vision, where typically the geometry of the weld pool is studied [5], or infrared thermography that allows a more suitable estimation of the temperature distribution on the workpice surface, which can be related to the welding quality [6, 7]. Acoustic monitoring of the signals generated during the process has given rise to other interesting monitoring proposals, for example in the audible and ultrasonic ranges [8], although the identification of defects with the acquired signal might prove not straighforward, thus requiring for example a statistical analysis of the acquired acoustic spectra [9].

B. Plasma optical spectroscopy applied to on-line welding monitoring

The analysis of the light emitted during welding processes such as arc or laser welding also allows a robust on-line welding monitoring, and it is a promising

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approach in this regard. Some initial proposals where based on the employment of photodiodes, which allow the integration of the radiation emitted over a specific wavelength range and its conversion to an electrical signal [10], thus establishing a correlation among the output monitoring signal and the perturbations generated during the process and reflected in the acquired light. These approaches have been typically limited to the study of a specific defect, for example lack of penetration [11], although there are some works where a wider defectology has been considered by also including optical filters in the setup [12]. Photodiode-based solutions have been also proposed for on-line process control, like the correction of a laser beam focus to obtain an optimal penetration depth [13].

When the captured plasma radiation is wavelength resolved, the plasma spectra can be anayzed via their continuum signal and the emission lines associated with the different species (elements contributing to the plasma, i.e. those forming the workpiece and the protection gas employed, in their different ionization stages). Although the plasma continuum radiation may give rise to a correlation with the welding quality [14], the typical procedure is to perform an analysis based on some selected emission lines, as their intensity is related to their participation in the plasma. The plasma electronic temperature T_e, is the common spectroscopic parameter used for monitoring, given the known correlation between T_e and the quality of the seams [15].

Although a more accurate estimation of T_e can be obtained using the Boltzmann-plot method [16], it has been common the employment of a simplified expression only involving two emission lines of the same species, given its reduced computational cost [17, 18]. To calculate T_e it is necessary to consider several processing stages, for example those indicated in Fig. 1.

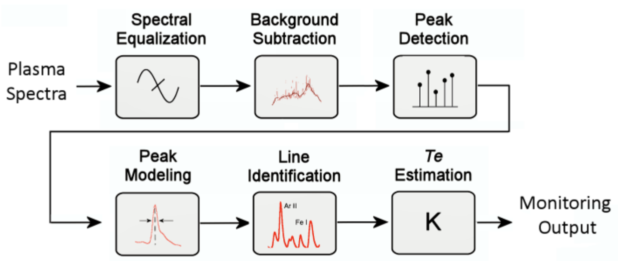


Fig. 1. Scheme of a possible processing design for the estimation of T_e.

The line identification step, which implies the association of a given emission line with its corresponding species, is probably the most complicated and critical process. It should be noted that several emission lines from different species can be found in very narrow spectral ranges and that the spectral resolution of the chosen spectrometer will also play a major role in this regard. Databases with spectroscopic information are typically employed [19], using the detected line central wavelength as the main parameter for its identification. However, given the ambiguous identifications that this simple approach might imply, more sophisticated approaches have been also proposed using text retrieval techniques [20] or linear and rank correlation [21].

III. PLASMA SPECTROSCOPY APPROACHES FOR ON-LINE WELDING MONITORING

The use of T_e as monitoring parameter has been proved suitable, although this solution exhibits some drawbaks, as the necessity of involving the emission line identification stage and the associated uncertainty derived from the chosen lines. It is worth noting that one of the main advantages of this approach lies in the reduced cost of the required setup, that can be formed by some input optics to collect the plasma radiation (e.g. collimator or cosine corrector), an optical fiber to guide the light from the vicinity of the plasma to a CCD spectrometer, which will be controlled by some hardware. The spectrometer is typically the most expensive device in this arrangement, and its cost will be directly related to its spectral resolution. Depending on the particular scenario, resolutions in the order of 0.3 to 1nm or even higher are typical. However, some strategies like the employment of the so-called sub-pixel algorithms in the modeling of the detected emission lines might help in reducing the negative effects of using low cost CCD spectrometers [22].

It is also possible to estimate T_e without the requirement of identifying the chosen lines via the so-called line-to-continuum ratio method [23]. In this case the intensity of an emission line and the intensity associated with the adjacent background radiation are used to estimate the plasma temperature, although their quotient can be also employed as the output monitoring parameter [14]. It has also been demonstrated that the integration of the plasma radiation over a given spectral range (*plasma RMS signal*) might be useful for monitoring purposes [24]. This approach, where the spectral window employed for the signal integration might be varied searching for an improved sensitivity, can be especially useful when new processes are studied, where there is no apriori knowledge of the elements of relevant emission lines to be analyzed.

Alternative methods to extract significant information from the plasma spectra have been also investigated. Sibillano et al. [25] proposed the use of the covariance mapping technique to study the dynamics of laser welding processes, analyzing the correlation among different elements for both optimal and defective seams. Synthetic spectra and optimization algorithms have been also used to estimate the participation of the different species in the plasma, and the correlation of this paramter to the appearance of flaws [26]. Sensor fusion solutions, based for example on photodiodes and cameras have also been reported for the monitoring of laser welding of alluminium alloys [27].

Directly related to plasma spectroscopy monitoring are colorimetric approaches. In this case a color space, which can be defined as a completely specified scheme for describing the color of light, typically involving three numerical values or coordinates [28], is employed. These three coordinates match the three kinds of photoreceptors (cones) resposnsible for color vision in human beings: S, M and L cones (for short, medium and long (wavelengths), associated with the detection of wavelengths with peaks at approximately 420 to 440, 534 to 545 and 564 to 580 nm). In a recent study the HSL color space parameters and the color temperature have been evaluated for welding monitoring. The latter parameter can be defined for a given light source as the temperature associated with a blackbody that emits radiation of the same chromaticity [29]. It has been demonstrated that, in some situations, the performance of these colorimetric parameters might exceed the results of the traditional spectroscopic approach. Fig. 2 shows an arc-welding seam (bead-on-plate) where two perturbations have been provoked: a variation in the stand-off distance (between the electrode and the plates) at t ≈ 3s and a protection gas shortage at t ≈ 7s. T_e has been calculated by means of the Boltzmann-plot method (black dashed line) with several ArII lines and the simplified equation only involving two ArII lines.

It can be observed that results are very similar for both T_e profiles, and while the first perturbation is clearly detected, the profiles do not exhibit any variation regarding the protection gas cut. The color temperature profile exhibits a dip associated with the first perturbation, while the second one is clearly detected, as some peaks appear in the profile after the gas cut.

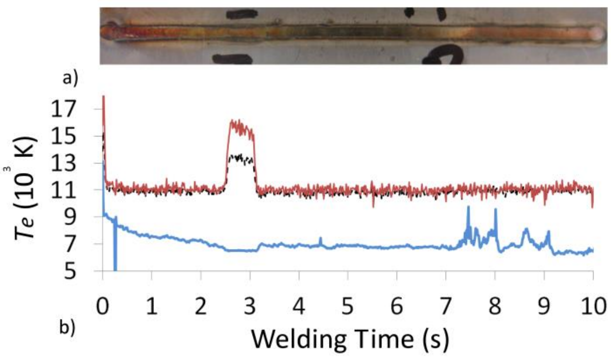


Fig. 2. Welding seam with two perturbations and their corresponding T_e profiles (Boltzmann-plot: black dashed line and simplied method: red line) and color temperature profile (blue line).

IV. ARTIFICIAL INTELLIGENCE SOLUTIONS FOR PLASMA SPECTRA PROCESSING

When T_e or a similar spectroscopic parameter is employed for on-line welding diagnostics, it is usually required a processing stage to automatically indicate whether a defect has appeared in the process. This has been normally performed via statistical analysis of the spectroscopic signals, but it is rather complicated to perform defect clasification with this kind of approaches. However, artificial intelligence (AI) solutions such as Fuzzy Logig, Artificial Neural Networks (ANNs) or Hierarchical Temporal Memories might help in this regard.

Fuzzy logic is probably the solution most originally employed in welding monitoring and control, whith several papers devoted to different implementations. ANNs have also atracted a lot of attention, due to its inherent ability to map non-linear problems and the possibility of allowing an output classification, among other features. An issue to be solved when an ANN is going to be used to process plasma spectra is the high dimensionality of the input data, which is usually a problem for these networks. Principal Component Analysis (PCA) can be used in a previous step to reduce the dimensionality of the available data by removing redundant data without loosing significant information. A proposal in this regard was presented in [26] where the original 2048-dimensional space was reduced to 14 components.

Feature selection algorithms like SFFS (*Sequential Forward Floating Selection*) have been also used in similar designs [30]. This algorithm is of special interest in this framework because a list of wavelengths listed in terms of their discrimination capability among the defined classes (correct welding and different defects) can be obtained.

Hierarchical temporal memories (HTMs) are a recent computational model proposed by Hawkins and Blakeslee [31], which is inspired in the structure of the human neocortex. HTMs exhibit some similiraties with ANNs, for example the consideration of two different working modes: the learning or training and the inference phases. However, time plays a major role in this case, because they are precisely the time variations of the input data what allows to identify their invariant patterns and to categorize them in a non-supervised manner. These features suggested their suitability for on-line welding monitoring, which was explored in [32] in the framework of a TIG (Tungsten Inert Gas) arc-welding process with 6 different categories defined: 0-correct welding, 1-lack of penetration, 2-excessive penetration, 3-misalignment, 4-different thickness, 5-tajectory deviation and 6-protection gas shortage. Fig. 3 depitcs the result of a HTM configuration defined to benefit the temporal poolers (classification). The classification rate lies in the vicinity of 86%, with some problems to discriminate among defective categories 2 and 4. It is worth noting that HTMs do not require an initial processing stage of data compression, thus accepting as input data the whole acquired plasma spectra.

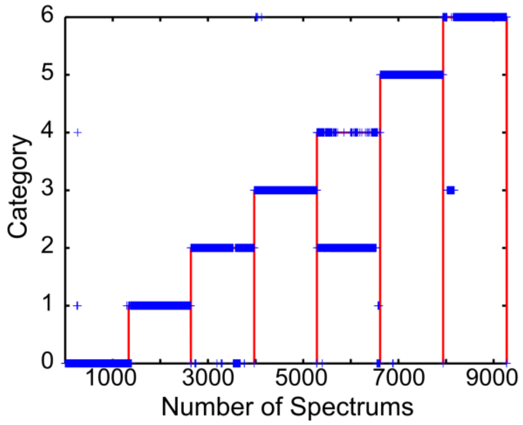


Fig. 3. Feasibility study of HTMs for welding on-line monitoring and defect classification. Results of the HTM output for categories: 0-correct welding, 1-lack of penetration, 2-excessive penetration, 3-misalignment, 4-different thickness, 5-trajectory deviation and 6-protection gas shortage.

V. EXAMPLES OF FIELD TRIALS IN DIFFERENT SECTORS

As previously commented, on-line monitoring is of great interest in those welding processes where quality standars are very demanding. A good example in this regard lies in the manufacturing of components for nuclear power stations. In particular, steam generators may include thousands of tubes that have to be welded in the so-called tube-to-tubesheet welding process. In [33] a plasma optical spectroscopy approach was proposed for the on-line monitoring of this process, where several tubes were analyzed during the orbital arc-welding procedure. One of the problems to be solved in this case was associated with the capture of the plasma radiation, as the configuration of the welding head made it difficult to perform it with a single optical fiber. A 600 µm (core diameter) bifurcated optical fiber with two cosine correctors as input optics was employed.

Fig. 4 shows a result of a test in a welding coupon, where a situation of lack of cleanliness was simulated by employing a gel for ultrasonic inspection in the tube-to-tubesheet interface. This resulted in a defective seam with a tunnel porosity that can be observed in Fig. 4(a), associated with the clear perturbations in the T_e profile from t ≈ 12s.

A good example of the potential of the spectroscopic analysis lies in the possibility of identifying (in real-time) the elements that are participating in the process and even to perform a semi-quantitative estimation of their participation. This may lead to some intesting applications in welding monitoring, like the on-line detection and quantification of some undesired elements that may affect the quality of the resulting seam.

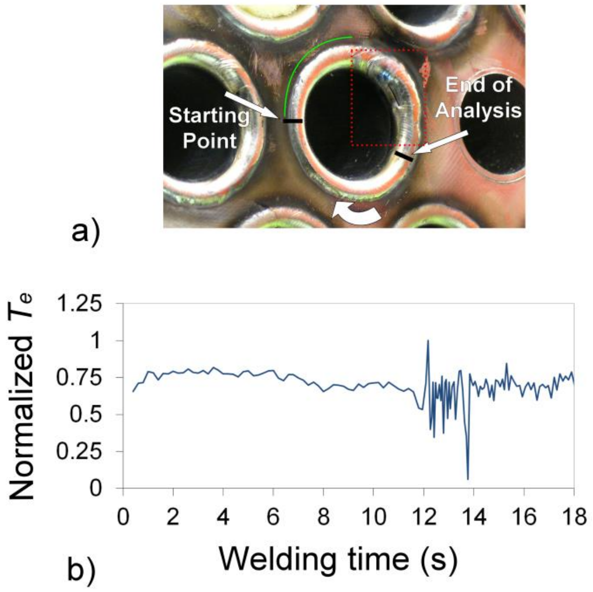


Fig. 4. Example of implementation in field trials for the nuclear sector: a) defective tube-to-tubesheet orbital arc-welding process; b) associated T_e profile indicating the appearance of the defect.

When USIBOR alloys are used for automotive manufacturing processes, it is a common practice to remove the outer later of aluminium from the vicinity of the joint using laser ablation. However, some aluminium might be still present in that region and its participation in the welding process and in the resulting joint would imply a deterioration in the mechanical proporties of the resulting workpiece. The selection of the appropiate spectrometer will enable the acquisition of the data related to some emission lines of AlI or AlII, thus allowing to perform a simple estimation of the Al participation by considering the intesities of those lines. In the framework of a R+D project developed by the Photonics Engineering Group (Universidad de Cantabria) for Gestamp/Solblank, a monitoring device able to estimate in real time the Al participation in the process and to reject or accept the seam by controlling one of the robots involved was designed and implemented.

Fig. 5 shows a study where several sheets were welded while the designed monitoring system estimated the relative participation of Al in the welding process (red line). After that, a study of the associated tensile strength was carried out, clearly indicating that when a specific amount of Al participates in the process, the mechanical properties of the welded joints are clearly worse, as can be observed in the tensile strength R_m graph (blue line).

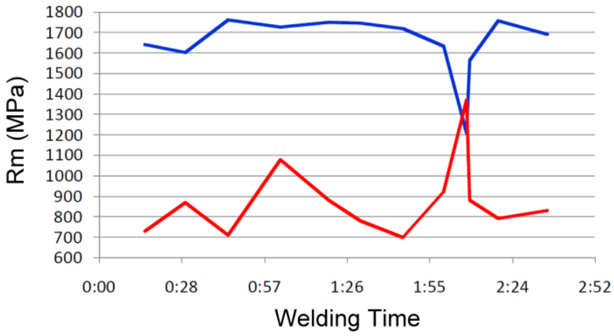
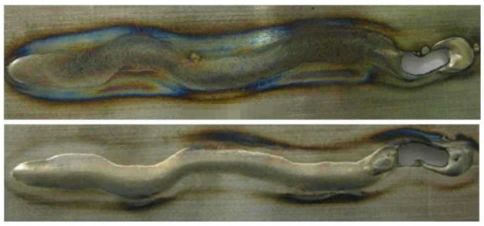
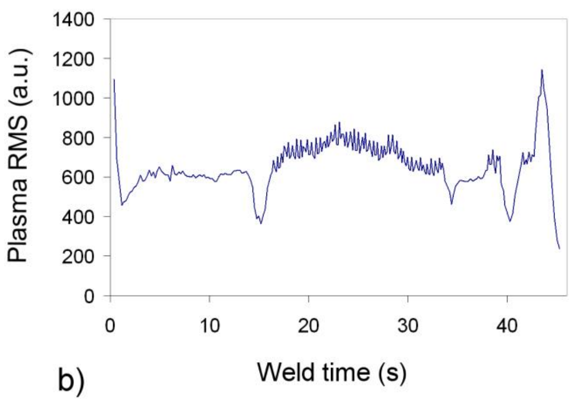


Fig. 5. Correlation between the presence of Al in the laser welding process (red line) and the tensile strength of the welded joint (blue line).



a)



b)

Fig. 6. Field trials in the aeronautics sector: a) arc-welding INCONEL 718 bead-on-plate seam with trajectory deviation; b) associated plasma-RMS signal.

A final example is presented in Fig. 6, correspoding to field trials performed in the facilities of the company ITP in Zamudio (Spain), devoted to the fabrication of components for aeronautics. Several defective situations were analyzed, and Fig. 6 shows a bead-on-plate on INCONEL 718 with a clear trajectory deviation. While analysis via electrical sensors do not clearly indicate this flaw [24], the basic approach delivered by the estimation of the plasma-RMS signal gives rise to a profile where the defects are clearly observed.

VI. CONCLUSIONS

In this paper a review of on-line welding monitoring via plasma optical spectroscopy has been presented. The basics and several spectroscopic approaches have been addressed, and a special focus has been devoted to processing techniques and AI solutions able to offer, not online real-time information about the process, but also additional features such as classification among different defective categories, which is a key point to achieve the final goal of these systems: an automatic control designed to avoid or prevent as much as possible the appearance of weld flaws during the process.

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REFERENCES

[1] C. Wu, M. Ushio, and M. Tanaka, “Analysis of the TIG welding arc behavior,” Computational Materials Science, vol. 7, no. 3, 1997, pp. 308-314.

[2] R. Ditchburn, S. Burke, and C. Scala, “NDT of welds: state of the art,” NDT & E International, vol. 29, no. 2, 1996, pp. 111-117.

[3] A. Tarn, and D. Hardt, “Weld pool impedance for pool geometry measurement: stationary and non-stationary pools,” Journal of dynamic systems, measurement, and control, vol. 111, 1989, pp. 545.

[4] L. Li, D. Brookfield, and W. Steen, “Plasma charge sensor for in-process, non-contact monitoring of the laser welding process,” Measurement Science and Technology, vol. 7, no. 4, 1996, pp. 615.

[5] G.-j. ZHANG, Z.-h. YAN, and L. WU, “Visual sensing of weld pool in variable polarity TIG welding of aluminium alloy,” Transactions of nonferrous metals society of china, vol. 16, no. 3, 2006, pp. 522-526.

[6] M. Speka, S. Matteï, M. Pilloz et al., “The infrared thermography control of the laser welding of amorphous polymers,” NDT & E International, vol. 41, no. 3, 2008, pp. 178-183.

[7] A. Cobo, J. Mirapeix, O. Conde et al., "Arc-welding process control based on back face thermography: application to the manufacturing of nuclear steam generators." pp. 65410F-65410F-11.

[8] Y. Wang, and P. Zhao, “Noncontact acoustic analysis monitoring of plasma arc welding,” International journal of pressure vessels and piping, vol. 78, no. 1, 2001, pp. 43-47.

[9] H. Gu, and W. Duley, “A statistical approach to acoustic monitoring of laser welding,” Journal of

Physics D: Applied Physics, vol. 29, no. 3, 1996, pp. 556.
[10] H. Park, S. Rhee, and D. Kim, "A fuzzy pattern recognition based system for monitoring laser weld quality," Measurement Science and Technology, vol. 12, no. 8, 2001, pp. 1318.
[11] J. O. Connolly, G. J. Beirne, G. M. O'Connor et al., "Optical monitoring of laser-generated plasma during laser welding." pp. 132-138.
[12] J. Mirapeix, R. Ruiz-Lombera, J. Valdiande et al., "Defect detection with CCD-spectrometer and photodiode-based arc-welding monitoring systems," Journal of Materials Processing Technology, vol. 211, no. 12, 2011, pp. 2132-2139.
[13] A. Cobo, F. Bardin, J. Mirapeix et al., "Optoelectronic device for non-invasive focal point measurement and control of the laser welding process," Measurement Science and Technology, vol. 16, no. 3, 2005, pp. N1.
[14] J. Mirapeix, A. Cobo, S. Fernandez et al., "Spectroscopic analysis of the plasma continuum radiation for on-line arc-welding defect detection," Journal of Physics D: Applied Physics, vol. 41, no. 13, 2008, pp. 135202.
[15] A. Poueyo‐Verwaerde, R. Fabbro, G. Deshors et al., "Experimental study of laser‐induced plasma in welding conditions with continuous CO2 laser," Journal of applied physics, vol. 74, no. 9, 1993, pp. 5773-5780.
[16] A. Ancona, V. Spagnolo, P. M. Lugara et al., "Optical Sensor for real-time Monitoring of CO2 Laser Welding Process," Applied Optics, vol. 40, no. 33, 2001, pp. 6019-6025.
[17] P. Sforza, and D. de Blasiis, "On-line optical monitoring system for arc welding," NDT & E International, vol. 35, no. 1, 2002, pp. 37-43.
[18] A. Ancona, P. M. Lugara, F. Ottonelli et al., "A sensing torch for on-line monitoring of the gas tungsten arc welding process of steel pipes," Measurement Science and Technology, vol. 15, no. 12, 2004, pp. 2412.
[19] Y. Ralchenko, A. Kramida, and J. Reader, "NIST atomic spectra database (version 4.0)," National Institute of Standards and Technology, Gaithersburg, MD, 2010.
[20] G. Amato, G. Cristoforetti, S. Legnaioli et al., "Progress towards an unassisted element identification from Laser Induced Breakdown Spectra with automatic ranking techniques inspired by text retrieval," Spectrochimica Acta Part B: Atomic Spectroscopy, vol. 65, no. 8, 2010, pp. 664-670.
[21] I. Gornushkin, M. Mueller, U. Panne et al., "Insights into linear and rank correlation for material identification in laser-induced breakdown spectroscopy and other spectral techniques," Applied spectroscopy, vol. 62, no. 5, 2008, pp. 542-553.
[22] J. Mirapeix, A. Cobo, C. Jaúregui et al., "Fast algorithm for spectral processing with application to on-line welding quality assurance," Measurement Science and Technology, vol. 17, no. 10, 2006, pp. 2623.
[23] G. J. Bastiaans, and R. A. Mangold, "The calculation of electron density and temperature in Ar spectroscopic plasmas from continuum and line spectra," Spectrochimica Acta Part B: Atomic Spectroscopy, vol. 40, no. 7, 1985, pp. 885-892.
[24] J. Mirapeix, A. Cobo, J. Fuentes et al., "Use of the plasma spectrum rms signal for arc-welding diagnostics," Sensors, vol. 9, no. 7, 2009, pp. 5263-5276.
[25] T. Sibillano, A. Ancona, V. Berardi et al., "Correlation analysis in laser welding plasma," Optics Communications, vol. 251, no. 1, 2005, pp. 139-148.
[26] J. Mirapeix, A. Cobo, D. González et al., "Plasma spectroscopy analysis technique based on optimization algorithms and spectral synthesis for arc-welding quality assurance," Optics express, vol. 15, no. 4, 2007, pp. 1884-1897.
[27] S. Katayama, S. Kawaguchi, M. Mizutani et al., "Welding phenomena and in-process monitoring in high-power YAG laser welding of aluminium alloy," Welding International, vol. 23, no. 10, 2009, pp. 753-762.
[28] D. A. Kerr, "The CIE XYZ and xyY Color Spaces," Issue, 2010.
[29] A. R. Robertson, "Computation of correlated color temperature and distribution temperature," JOSA, vol. 58, no. 11, 1968, pp. 1528-1535.
[30] P. Garcia-Allende, J. Mirapeix, O. Conde et al., "Spectral processing technique based on feature selection and artificial neural networks for arc-welding quality monitoring," NDT & E International, vol. 42, no. 1, 2009, pp. 56-63.
[31] J. Hawkins, and S. Blakeslee, On intelligence: Macmillan, 2007.
[32] L. Rodriguez-Cobo, R. Ruiz-Lombera, O. M. Conde et al., "Feasibility study of Hierarchical Temporal Memories applied to welding diagnostics," Sensors and Actuators A: Physical, vol. 204, 2013, pp. 58-66.
[33] A. Cobo, J. Mirapeix, F. Linares et al., "Spectroscopic sensor system for quality assurance of the tube-to-tubesheet welding process in nuclear steam generators," Sensors Journal, IEEE, vol. 7, no. 9, 2007, pp. 1219-1224.