Optical Methods for On-line Quality Assurance of Welding Processes in Nuclear Steam Generators

Adolfo Cobo, Jesús Mª Mirapeix, David Solana[1], Alfonso Álvarez-de-Miranda[1], Pilar-Beatriz García-Allende, Olga Mª Conde and José Miguel López-Higuera
Photonics Engineering Group at the University of Cantabria,
[1]Equipos Nucleares, S.A. (ENSA)
Spain

1. Introduction

The manufacturing of steam generators relies heavily in many different processes of welding, involving a wide range of materials, welding procedures and requirements. Quality assurance is of paramount importance in these processes, and in the case of the nuclear industry, even more rigorous quality control procedures, according to the nuclear safety regulatory rules and customer specifications, are required.

The currently accepted procedure for quality control is based on the rigorous control of the welding parameters, such as the heat input, welding speed, material geometry, surface preparation and cleanness, etc. However, it is known that the physics involved in these processes is extremely complex, and the efforts aimed at developing a reliable formulation of the relationships between the process parameters and a defect-free welding seam have mostly failed (Wu et al., 1997), with only some success in the prediction of stress and distortion of the joined piece (Dong, 2005).

For that reason, quality assurance in welding processes is typically performed by means of procedure trials, where the suitable welding parameters are established and used later in production. However, as there is no guarantee that a free-defect welding is always achieved, non-destructive testing (NDT) techniques are routinely applied in different stages of the manufacturing process. These techniques (liquid penetrant, magnetic-particle, ultrasonic, X-Ray, Eddy current testing …) are quite effective to validate the quality of the welds, but most of them are difficult to automate, require complex procedures and take a significant amount of the production time.

Although *off-line* NDT procedures can not be avoided in those critical applications, there is still a great interest in the possibility of *on-line* monitoring and control of the welding process. This approach allows the early repair (or even the real-time correction) of defects, resulting in a reduction of the manufacturing time and costs.

This paper deals with one particular approach for on-line sensing, namely, the spectroscopic detection and processing of the light generated by the process itself. A great deal of information about the real-time behaviour of the welding process can be extracted through

the analysis of the spectroscopic signal, including the detection and classification of defects. This approach is valid in all processes in which thermal plasmas are generated, for example, arc and laser welding in the keyhole regime, which have strong optical emission in the visible range. In this work, the proposed technique has been validated for the arc welding process and several alloys.
The field trials, performed in the production facilities of Equipos Nucleares, S.A. (ENSA), have been focused on one particular process: the tube-to-tubesheet welding in large steam generators for the nuclear industry. This is a particularly demanding process in terms of quality control due to the huge number of tubes involved and the severe consequences of difficult-to-detect defects like small porosities. Although the current production methods result in rare occurrences of such defects, their detection at late stages of the manufacturing process (for example, during the high-pressure hydraulic test of the finished steam generator) requires time consuming reworks. Many welding procedures in the manufacturing of components for the nuclear industry can also benefit from on-line monitoring. Figure 1 shows a sector of a large steam generator's tubesheet with more than 10,000 tubes to be welded as part of the manufacturing process.

Fig. 1. Tubesheet of a steam generator for the nuclear industry

In the next section, a brief introduction to the different approaches for on-line monitoring of the welding processes is presented. Section 3 provides details about the fundamentals of the plasma emission spectroscopy. Different methods to adapt the spectroscopic approach for welding diagnosis are also proposed, with the aim of real-time defect detection capabilities. The implementation of the sensor system is discussed in section 4, in particular, different solutions to the non-invasive capture of light in a production environment are provided.

Section 5 presents the results obtained with the different sensor implementations and spectroscopic processing techniques that have been tested in field trials for the monitoring of the tube-to-tubesheet welding process of large steam generators for nuclear power plants. Finally, some conclusions and future lines of work are discussed.

2. On-line monitoring of the welding processes

The importance of on-line monitoring of the welding processes has been recognised long time ago, even if off-line NDT procedures can not be avoided. Several technologies have been proposed and investigated for this task, with different level of success and commercial adoption. For example, today is very common for automated welding procedures to be guided by seam tracking devices. They are usually based on the projection of a laser line on the workpiece, while a video camera take an image of the surface profile to guide the trajectory of the torch or the laser beam (Bae et al., 2002). Voltage sensors to automatically adjust the current in arc welding processes are also routinely used. Although these approaches help to improving the quality, there is no real assessment of the resulting quality and the presence of defects in the weld seam. For this task, other approaches have been investigated but not widely adopted in production so far.

One possibility is the capacitive sensing between the welding nozzle and the workpiece, which has been investigated in (Li et al., 1996) for the laser welding process in the keyhole regime. This measurement is expected to give a constant value for a uniform seam with constant parameters, and any deviation can be attributed to a potential defect. This technique has demonstrated a detection rate over 95% of common defects like poor penetration, hole formation (as small as 0.1mm), miss-tracking, etc. However, as one single variable is provided and processed, this method makes it difficult to classify and distinguish defects.

Acoustic detection gives also real time information about the process. It has been proved that the arc and laser welding produces acoustic emission in the audible and ultrasonic ranges that can be correlated with the onset of defects (Wang & Zhao, 2001). As with the previous technique, it is however difficult to discriminate among different defects, although a statistical analysis applied to the spectra of sound has demonstrated some success in predicting the weld quality (Gu & Duley, 1996).

Thermography is also a powerful monitoring technique. It offers advantages over classical artificial vision systems in the visible range, as there is a more direct estimation of the temperature distribution over the workpiece, which is clearly a magnitude directly related to the welding quality. A particular case is the single-point temperature measurement, which is a robust approach when used in a production environment, although with limited capabilities (Wikle et al., 2001). Thermographic imaging (2D) is a better method which provides spatial and temporal resolution (Cobo et al., 2007), but the availability of robust infrared cameras for the industrial environment is still limited.

Plasma optical spectroscopy has also proven to be a promising solution. It extracts rich information about the process from the strong optical emission of the thermal plasma generated by the process. Some of the advantages of this technique are the following:

- The optical spectrum includes a continuum of radiation and emission lines from the atomic species found in the plasma. Both of them (specially the emission lines) offer information about the plasma and therefore about the welding process. As the intensity of the lines is related to the level of participation of the chemical elements (and their ions) in the plasma, and many lines from several elements are typically found even in a short wavelength range, it is possible to derive detailed information about the behaviour of the process.

- The sensor can be a simple non-invasive optical fibre located at a distance from the arc or beam, while the optoelectronic instrumentation can be dozens of metres away in a controlled environment. The instrumentation of a monitoring system comprises a spectrometer and a processing unit. With the proper optics, the end of the optical fibre can be placed also far away from the pool and protected from fumes or projections.
- Due to the strong light emission from the plasma, a simple and inexpensive CCD (Charge Coupled Device)-based spectrometer can be used to provide high-speed and real-time analysis of the welding quality.
- The optical fibre is intrinsically immune to the strong electromagnetic interferences (EMI) associated with the welding process.
- It does not require any modification of the procedure setup.

However, this approach is not free of drawbacks. One is that the classical processing technique of the acquired spectra is the determination of the electronic temperature of the plasma (Te). This involves a series of steps, including the identification and characterization of the emission lines, which require significant processing power. On the other hand, the relationship between Te (and other spectroscopic variables) with the resulting quality is not clear in many cases, and always difficult to model, nevertheless.

For that reasons, the works presented in this chapter try to optimize the spectroscopic approach for real-time quality monitoring, including the evaluation of more efficient processing techniques and exhaustive experimental works to improve the detection and classification of defects. Next section introduces the fundamentals of the proposed spectroscopic method and different approaches of spectroscopic analysis.

3. Spectroscopic methods for on-line welding monitoring

The plasma emission optical spectroscopy is based on the wavelength-resolved analysis of the light generated by the thermal plasma, which is naturally produced by some welding procedures such as arc and laser welding. The "hardware" of the sensor system is simple: it comprises an optical fibre to capture the plasma emission from the process, and a remote spectrometer to obtain spectral-resolved information. The captured spectrum is then processed to obtain relevant information. The common approach when using plasma spectroscopy in a welding sensor and monitoring system is to calculate the plasma electronic temperature Te, as it is known that there is a correlation between the resulting profiles of this parameter and the quality of their associated welds (Poueyo-Verwaerde et al., 1993). Figure 2 shows the processing steps needed with this "classical" approach of spectroscopic analysis.

Determination of Te is typically carried out by means of the information associated with two different atomic emission lines, of the same element in the same ionization stage

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

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 and κ the Boltzmann constant.

Equation (1) is a simplification of the so-called Boltzmann-plot, which allows the use of several emission lines for the Te calculation process

$$ln\left(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}\right)=ln\left(\frac{hcN}{Z}\right)-\frac{E_m}{kT_e} \quad (2)$$

where h is the Planck's constant, c is the light velocity, N the population density of the state m and Z the partition function. The representation of the left-hand side of Equation (2) versus E_m has a slope inversely proportional to Te. Equation (2) is derived from the Boltzmann equation

$$N_m=\frac{N}{Z}g_m\, exp\left(\frac{-E_m}{\kappa T_e}\right) \quad (3)$$

and the expression that relates the intensity of a given emission line I_{mn} to the population density of the upper level N_m,

$$I_{mn}=N_m A_{mn} h\gamma_{mn} \quad (4)$$

The use of Equation (3) is valid when the plasma is in the state known as Local Thermodynamic Equilibrium (LTE) (Griem, 19643). The condition for LTE is satisfied when

$$N_e \geq 1.6\times 10^{12} T_e^{1/2}(\Delta E)^3 \quad (5)$$

where N_e is the plasma electronic density and ΔE the largest energy gap in the atomic energy level system.

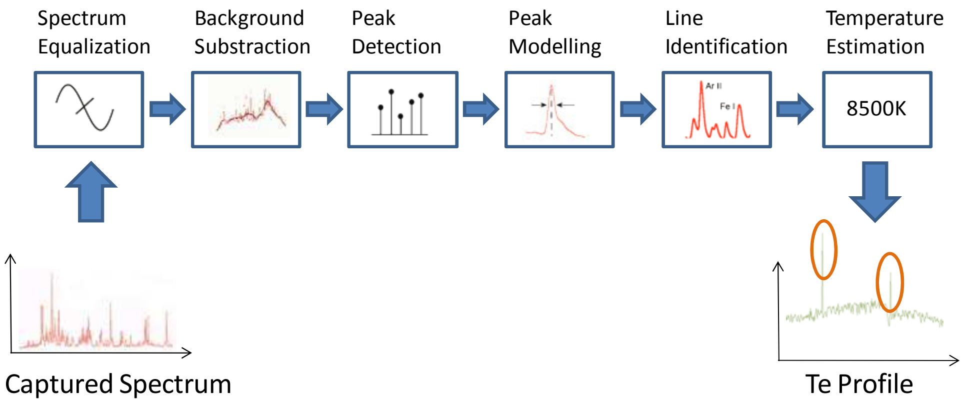


Fig. 2. Classical spectroscopic processing chain to obtain the profile of electronic temperature for a weld seam, from which defect formation can be estimated

Using either a pair of lines or a wider set to calculate the Boltzmann-plot, it is necessary to select and identify the lines for a specific element, and measure their centre wavelength, spectral width and intensity. This is not an easy task due to the presence of noise, overlapping lines, and calibration issues of the spectrometer, which could result in the wrong identification of the atomic element or appreciable errors in the estimation of the light intensity emission. Furthermore, iterative techniques like Levenberg-Marquardt (Robinson et al., 1998) are typically used for peak characterization. However, their high computational cost makes these solutions unsuitable for a real-time monitoring and control system (Ancona et al., 2001).

3.1 Efficient estimation of the electronic temperature of the plasma

One possibility is the non-recursive and time-efficient analysis of the lineshape. For this task, the linear phase operator (LPO), a sub-pixel technique, has been proposed (Mirapeix et al., 2006). Figure 3 (left) shows a captured spectrum for a TIG (Tunsgten Inert Gas) welding in which several elements (Iron, Manganese…) have been identified in real time.

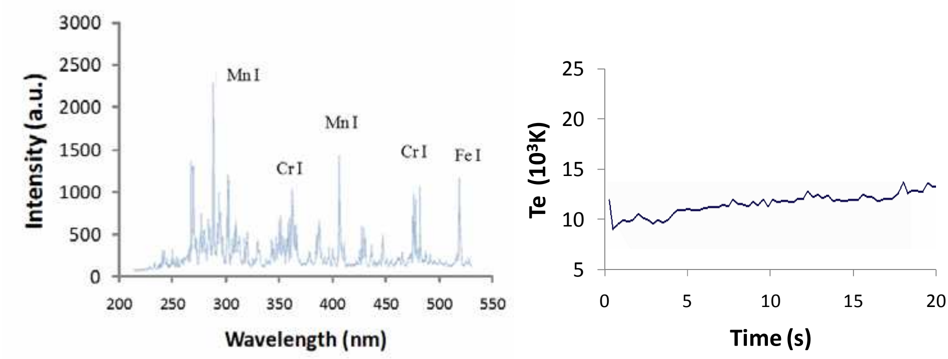


Fig. 3. Spectrum of a TIG welding in which the emission lines of some of the steel constituents and shielding gas have been identified and measured in real time (left). Calculation of the electronic temperature of the plasma (Te) for the case of a seam without defects (right)

Once the electronic temperature is calculated, a complete "profile" for the entire seam can be obtained. Both the absolute value and the relative variations of Te give information about the process. For a welding seam with constant parameters, Te is expected to be within a particular range of values; and any unexpected variation can be attributed to a perturbation of the process, and hence to a potential defect. Several statistical analysis techniques have been proposed to detect in real time any possible defect (Ancona et al., 2004) (Bebiano & Alfaro, 2009). Fig. 3 (right) shows an example of a temperature profile for a correct weld seam with nominal parameters.

In the following sub-sections, several techniques for automatic and real-time defect detection are explored. They try to substitute the estimation of the electronic temperature for a simpler spectroscopic variable, or even to correlate directly the captured (raw) spectra with the occurrence of defects. The aim is the real-time identification of defects with a simple and efficient technique that can be implemented in a real production environment, in particular, for the manufacturing of large steam generator for nuclear power plants.

3.2 Spectroscopic analysis based on the background radiation

The background radiation (continuum) is usually ignored or removed from the captured spectrum. It is generated by recombination processes of free electrons and ions, and by the

Bremsstrahlung effect, and does not offer specific information about particular atomic species. However, it can be helpful to simplify the calculation of Te or to detect defects.
For example, an alternative method to compute Te is the line-to-continuum ratio method (Bastiaans & Mangold, 1985). In this case, Te is calculated using the relation between a single emission line intensity (integrated over the line profile) ε_l and the intensity of the adjacent background radiation (non-integrated) I_c:

$$\frac{\varepsilon_l}{I_c}(\lambda) = 2.0052 \times 10^{-5} \frac{A_{mn} g_m}{Z_i} \frac{1}{T_e \xi} \exp\left(\frac{E_i - E_m}{kT_e}\right) \frac{\lambda}{\Delta\lambda} \qquad (6)$$

where Zi is the ion partition function, ζ the free-bound continuum correction, E_i the ionization potential and Δλ the wavelength bandwidth. Although the calculation of Te is not straightforward and an iterative method is required, the ratio ε_l/I_c can be directly used as the monitoring signal, given that there is a direct relation between this quotient and Te. If only this ratio is to be determined, this method is easy to implement as the selected emission line does not need to be identified.
However, it has been demonstrated that no all emission lines are good candidates to infer information about the welding process (Mirapeix et al., 2008). For that reason, a previous process of line selection using the Sequential Floating Forward Selection (SFFS) algorithm is proposed (García-Allende et al., 2009). This algorithm is widely applied to reduce the dimensionality, i.e., the number of wavelengths, of spectral data prior to their interpretation (Ferry et al., 1994). In this case, previously capture spectra are labelled according to their associated defects, and the optimum spectral band in terms of defect classification is obtained by the algorithm. These wavelengths are then used as the spectroscopic monitoring signal for the process. Fig. 4 shows how the processing steps are reduced with this approach.

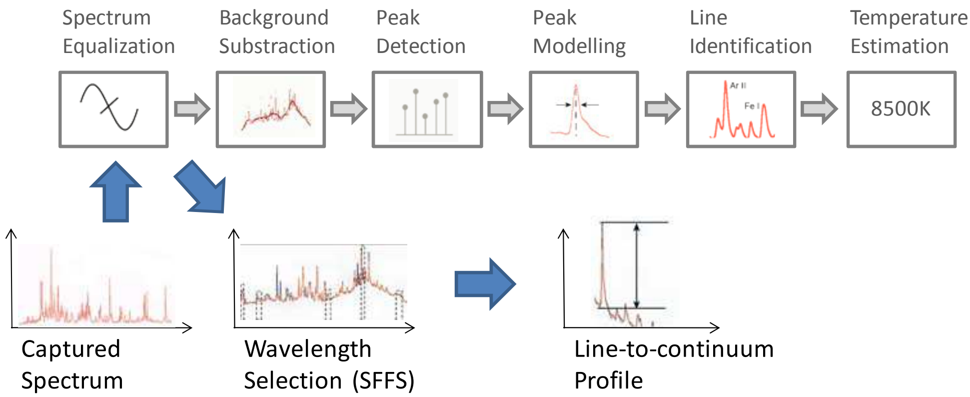


Fig. 4. Spectroscopic processing using SFFS for line selection and line-to-continuum as the monitoring variable

Once the optimum emission lines are selected *a priori*, the monitoring task involves the measurement of the emitted light at that particular wavelength with respect to the surrounding background level. Any variation of this ratio for a constant parameters welding can be analyzed and related to a particular defect.

Another possibility for defect detection is the analysis of the shape of the continuum radiation. It has been demonstrated that this background radiation has a wavelength of maximum emission, and this wavelength is fairly stable for a defect-free, constant-parameters welding process. Thus, the real-time tracking of this wavelength can be an indicator of defect formation.
The implementation of this solution is quite simple, as the only processing requirement is the extraction of the plasma background signal from the acquired spectra. Two different alternatives have been explored in this regard. An initial approach has been carried out by means of a smoothing algorithm, which was already implemented in (Mirapeix et al., 2006) to perform the background subtraction stage. The only parameter to take into account is the size (in spectral bands) of the moving window. Modelling of the plasma background has also been attempted by means of a low-pass filter. A frequential analysis of the welding spectra was initially conducted to remove the contribution of the emission lines. After the filtering process, the resulting background signal is modelled as a blackbody radiation via the Planck function:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\left(e^{\frac{hc}{kT\lambda}} - 1\right)} \tag{7}$$

where T is the temperature that has to be previously obtained by means of

$$\lambda_{max} = \frac{2.9 \cdot 10^6}{T} \tag{8}$$

where λ_{max} is the wavelength associated with the maximum intensity of the plasma spectrum after the filtering process. Processing needs with this approach are much simplified, as can be seen in Figure 5 with respect to the classical approach of Te estimation (Mirapeix et al., 2008).

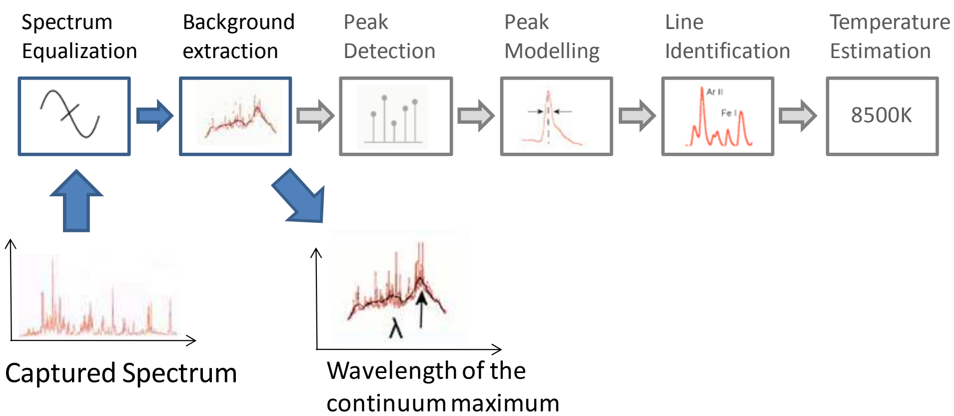


Fig. 5. Spectroscopic processing using the estimation of the wavelength of maximum radiation in the background signal

The results obtained in field trials with these two continuum-based methods are presented in section 5.

3.3 Defect detection through the RMS spectroscopic signal

Another alternative has been explored to avoid the use of the plasma emission lines. The plasma RMS (Root Mean Square) signal is determined by considering the spectral intensity of the plasma spectra over a specific spectral window, thus being directly related to the process heat input and behaviour (Mirapeix et al., 2010). This approach is directly related to other based on the use of photodiodes for process monitoring (Park et al., 2001).
The processing scheme required for this option is very simple (see Figure 6), it may allow fast implementations independently of the particular process and material to be welded, and the obtained results show that there is a good correlation between it and the quality events identified on the seams.

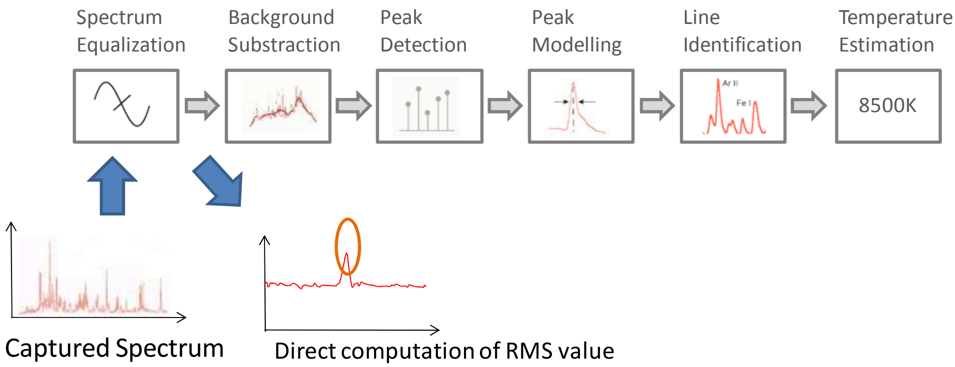


Fig. 6. RMS spectroscopic signal as a defect indicator

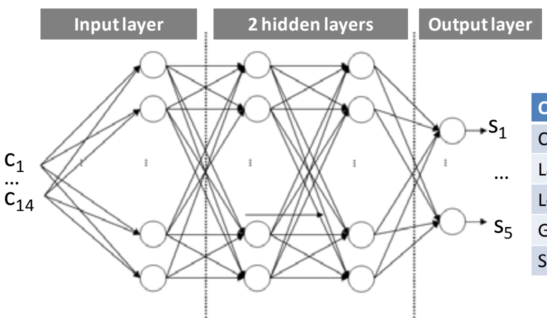
3.4 Direct defect detection by means of artificial neural networks

Finally, we propose another processing technique based on the use of artificial neural networks (ANN) to achieve classification of defects from the raw spectra captured by the spectrometer. This approach is an interesting solution due to the lack of a suitable mathematical model of the welding process and when abundant experimental data is available from the specific welding process to train the network.
However, the amount of information to process by the ANN, considering a real-time system, could be a mayor drawback. For example, a typical spectroscopic system consists of 2048 wavelengths (number of pixels of the spectrometer's CCD used), with an average of 50 spectra captured per second. For this reason, it would be desirable to reduce the number of wavelengths to process, which can be done taken into account that not all the spectral lines offer relevant information about the process.
Two techniques are proposed for the task of reducing the amount of spectral information that feeds the ANN. The first one is the Principal Component Analysis (PCA), which performs redundancy removal and data compression simultaneously (Workman & Springsteen, 1998). Performing data compression implies reducing the number of required components, as much as possible, without losing relevant information. This is accomplished by the expression of the captured spectra in a different vectorial basis which is obtained in

such a way that the new basis vectors are those directions of the data containing the most relevant information. The result of the process is a smaller data set including most of the information. Selecting a set of about 15 values, a compression rate of 99% is achieved without significant loss of defect detection capabilities (Mirapeix et al., 2007).

The second technique is the Sequential Floating Forward Selection (SFFS) algorithm already mentioned. One important advantage of SFFS is that the output of this algorithm is a selection of the most discriminant wavelengths, as opposed to PCA, which gives a set of discriminant features that cannot be associated with any particular spectral band. For this reason, by applying SFFS to an experimental set of data from the same welding process, it is possible to automatically select a reduced number of optimum wavelengths to monitor for defect detection. Experiments confirm that the selected wavelengths are those of the significant elements of the material to be welded or those of the shielding gas. In the case of TIG welding of steel with Argon gas, for example, selected wavelengths are typically the emission lines of Iron, Manganese and Argon. It has been demonstrated that the defect-detection and classification capabilities are not significantly reduced even when only 10 wavelengths are supplied to the ANN (García-Allende et al., 2008).

The proposed architecture for the ANN is a multilayer feed-forward network with a back-propagation learning algorithm. Its main performance metrics is (apart from computation efficiency for real time applications) the classification error, that is, its ability to give the correct defect indication for a given spectrum at its input. During the training stage, spectra of correct welds and all the possible defects have to be supplied to the neural network. In this step the network iteratively adjusts its parameters (weights and biases) in order to produce an output that matches the expected results. Several experiments have been realized to determine the appropriate number of hidden layers, the number of neurons or processing elements and the topology. ANN topologies with one and two hidden layers and with a number of neurons in each layer from 30 to 50 have been tested. The neurons in all layers have a log-sigmoid transfer function. Figure 7 shows the proposed architecture for an ANN, with five outputs that signal a correct welding or four possible situations: slight lack of penetration, severe lack of penetration, reduction of shielding gas flow and low welding current. The capability of this approach to detect these defects has been tested experimentally in the laboratory on TIG welding of steel plates. A better performance that the analysis of the electronic temperature profiles for defect detection has been found (García-Allende et al., 2009a).



Ouput	s_1	s_2	s_3	S_4	s_5
Correct welding	1	0	0	0	0
Lack of penetration	0	1	0	0	0
Low welding current	0	0	1	0	0
Gas flow reduction	0	0	0	1	0
Slight lack of penetration	0	0	0	0	1

Fig. 7. Architecture of a ANN to classify between four possible welding conditions that lead to defect formation

In summary, several techniques of spectroscopic analysis offer the possibility of real-time automatic quality assurance of the welding process. In the next section, the implementation of these techniques in a spectroscopic sensor system able to work in a real industrial production environment is addressed.

4. Spectroscopic sensor implementation for production environments

A spectroscopic sensor, as described above, needs a CCD spectrometer and a processing unit that can be placed far away from the welding point, thanks to the light transmission capabilities of the optical fibre. The generic architecture of a spectroscopic sensor system is shown in Figure 8.

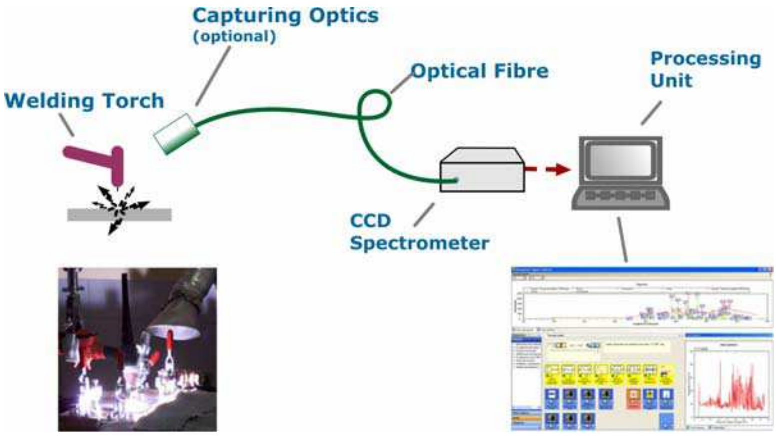


Fig. 8. Spectroscopic sensor architecture

However, one end of the optical fibre must be located close to the generated plasma, and this can be challenging in a real industrial scenario, due to reliability issues, heat, projections, fumes, accessibility of the process and workplace configuration. In laser welding this can be solved by using the optical port usually available at the laser head. In this case, the plasma emission is co-axially captured from the plume through the focusing lens of the laser beam. For arc welding, two non-intrusive solutions for the capture of light have been proposed. The first one is suitable for TIG and MIG torchs, and it is based on the embedding of the bare optical fibre tip in one of the shielding gas nozzle exits. The gas flow has a cooling effect upon the fibre, also preventing possible weld pool projections from interfering with the light capturing process. It has been demonstrated that, although the fibre suffers some external deterioration due to the welding process, the fibre core remains unaffected, and the fibre effectively collects the light even after 100 welding tests (total welding time of 800 seconds). Measurements of the fibre transmission after several welding processes have shown the appearance of some wavelength-dependent losses in the UV region due to the intense plasma radiation. However, although special solarization-resistant fibres could be used to avoid this phenomenon, the effect of these losses is not especially relevant, as the fibres employed in our tests have proved to be suitable for plasma spectroscopic analysis. Figure 9 shows a photograph of one embedded fibre tip in a TIG welding torch and a microscope view of the fibre’s end before and after intensive welding trials (Mirapeix et al., 2007a).

Fig. 9. Optical fibre embedded in a TIG welding torch (left), and view of the fibre's end before and after more than 100 welding trials

The second approach has been developed specifically for orbital TIG welding of tubes to the tubesheet of steam generators. In this case, the welding torch includes a complex mechanism to automatically perform the orbital weld seam over the tube's perimeter. The entire mechanism is enclosed in a protective shield with the shielding gas, being difficult to collect the light from the moving arc with the optical fibre. The proposed solution is depicted in Figure 10. Two cosine correctors are placed at the end of two optical fibres (silica fibres with a core diameter of 600µm), which are attached to the welding torch trough two holes in the steel case. The cosine-corrector, whose difussing material is Spectralon, is a spectro-radiometric optics designed to collect light over 180º, which is of special interest given the moving arc. The light from the two fibres is combined with an optical 2x1 coupler and sent to the CCD spectrometer. Although this optical setup results in some variation of the overall collected light intensity when the electrode moves along the circular path, the relative nature of the spectroscopic processing approach does not affect to the capability of defect detection (Cobo et al., 2007a).

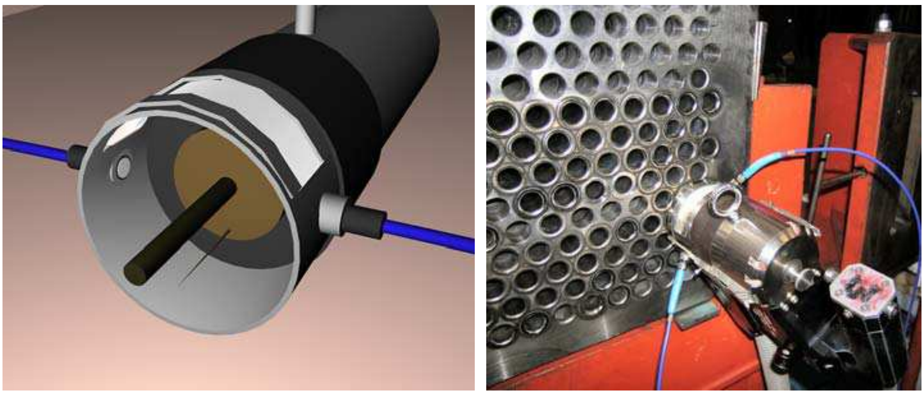


Fig. 10. Optical setup for efficient and non-invasive light capturing in the orbital TIG welding of tubes

In the next section, the results in field trials in a production environment of the proposed spectroscopic sensor system with the different processing approaches mentioned above are presented.

5. Field trials in the manufacturing process of steam generators

The above proposed techniques have been tested in the welding trials and qualification of large steam generators for nuclear power plants, in particular, for monitoring and real time defect detection in the tube-to-tubesheet TIG welding process in the facilities of the company ENSA (Equipos Nucleares S.A.) in Maliaño, Spain. The INCONEL-690 tubesheet cladding mock-ups include tubes with a diameter of 19.2 mm and a thickness of 1 mm. The welding system is formed by a Model 227 Power Supply (Arc Machines Inc.) attached to a Model 96 Tube-to-tubesheet automated weld head, designed to perform the required orbital welds, as described above. The welding current was pulsed at 50Hz with a maximum of 60A. Argon and Helium where used as shielding gases, with a mixture of 40% and 60% respectively. The electrode is made of tungsten, and the total duration of the welding process for each tube is about 30 seconds.
The light capturing optics consists of two optical fibres (Ocean Optics P600-UV-VIS, 4 metres long) with cosine correctors, an optical coupler, and a CCD spectrometer (Ocean Optics USB2000) with 2048 pixels and a resolution of about 0.2 nm in the range from 195 to 530nm (blue-green zone of the visible spectrum).

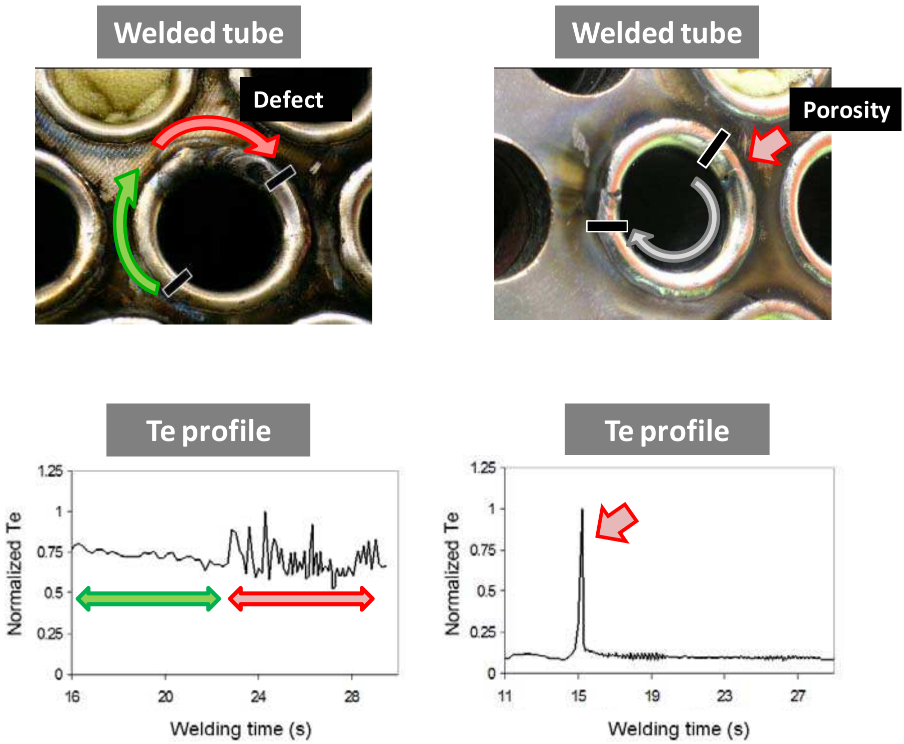


Fig. 11. Detection of defects by means of the Te profile. Left: defective weld seam due to shielding gas shortage. Right: small porosities

Due to the rare occurrence of real defects during the manufacturing process, deliberate change of process parameters and perturbations have been produced in weld test coupons

to simulate defects, like porosities and lack of penetration. The formation of defects has been validated by means of PT (Penetrant Testing) procedures.
The results from the application of the different spectroscopic processing techniques described above are presented in the rest of this section.

5.1 Defect detection using the real-time estimation of the electronic temperature of the plasma

The spectroscopic processing technique described in section 3.1 has been tested in a production environment with the aim of automatically detect and classify defects occurring during the orbital welding of INCONEL-690 tubes. The example spectrum and the electronic temperature profile of a defect-free weld seam already shown in Figure 3 correspond to these experiments. The initial and final parts of the seam have been removed because welding current is not constant at these points. It can be seen that the value (around 12,000K) is fairly stable, an indication of a correct welding.
In Figure 11, two defects with their corresponding temperature profile are shown. To the left, a shortage of the shielding gas starts in the middle of the seam, producing a defective welding, which is clearly visible in the Te profile. To the right, one point of the tube's edge has been deliberately contaminated, resulting in a small area of porosities. The Te profile shows a clear indication of this defect.

5.2 Defect detection by means of the optical background radiation

As described in section 3.2, the background radiation (continuum) of the plasma emission can be analysed to obtain warnings of defect formation. The tracking of the wavelength of maximum emission of the background radiation has also been applied to the tube-to-tubesheet welding process. In Figure 12, a weld seam is shown with a deliberate defect: the operator produced a perturbation in the shielding gas by blowing into the welding torch head at t ≈ 24 sec. It can be seen a sudden perturbation of the wavelength of maximum background radiation, while its value is stable when no defects are being produced. The constant variation of the wavelength (with negative slope) shown in Figure 12 has not been observed in other experiments with different welding processes, and a possible explanation is that the orbital welding produces variations in the global light intensity captured along the weld seam. This method, not being relative like the Te estimation, is more affected by this problem.

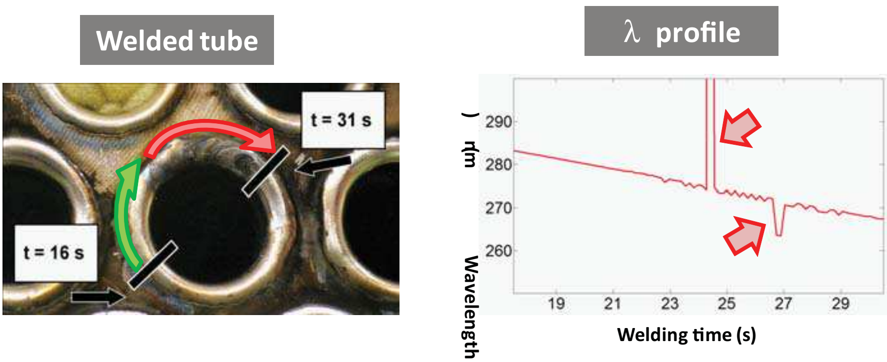


Fig. 12. The tracking of the shape of the background radiation allows detecting defects like perturbation in the shielding gas

The line-to-continuum method, already presented in section 3.2, is a relative method that also takes into account the background radiation. Figure 13 shows one of the experiments in which porosity was formed. The upper graph shows the line-to-continuum ratio for the spectral band of 404.14nm, corresponding to the neutral species Mn I, and previously selected by the SFFS algorithm as a significant wavelength. However, the zone with the porosity (red box) shows no clear indication of the defect. The lower graph, however, corresponds to the wavelength of 422.84nm (ion Fe II) and shows a clear indication of the defect. For that reason, it is important to have previous experimental data to determine the best wavelengths for a particular defect.

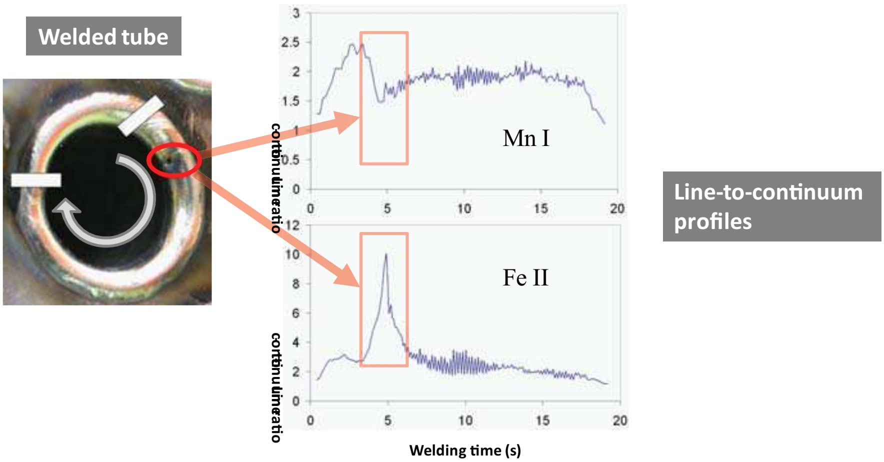


Fig. 13. Tracking of the line-to-continuum ratio for two selected wavelengths

5.3 RMS spectroscopic signal as a defect indicator

The real-time calculation of the Root Mean Square (RMS) of the captured spectrum is related to the process behaviour and the heat input, as explained in section 3.3. The capability of this technique to detect common defects has also been tested in field trials for the same welding process (Mirapeix et al., 2010).

In Figure 14, the resulting RMS profile for a defective weld seam is shown. To the left, a welded tube with a porosity (produced by including contamination in the tube-to-tubesheet interface) is shown. The RMS profile shows a sharp peak associated with this porosity. In addition, the rest of the profile shows periodic perturbations that also indicate that the contamination was also present at that section. In Figure 14 (right), a defect was simulated by disturbing the protection gas flow, thus provoking a clear defective section in the welded tube. There is a correlation between the correct seam (highlighted in green) of the analyzed section and the defective area (red), and their corresponding plasma RMS signals. While the former has an associated plasma RMS profile without perturbations, the latter shows rapid variations of the signal indicating the occurrence of a defect.

These experiments confirm that all the spectroscopic processing techniques are able to detect typical defects found in the TIG welding process of tubes for steam generators. Although the field trials have been limited to welding of INCONEL alloys, in-lab experiments with steel plates offer the same performance. In fact, one important advantage of the spectroscopic method is that it is quite independent of the material and the process parameters, provided that the material to be welded is known and appropriate emission lines are selected *a priori*.

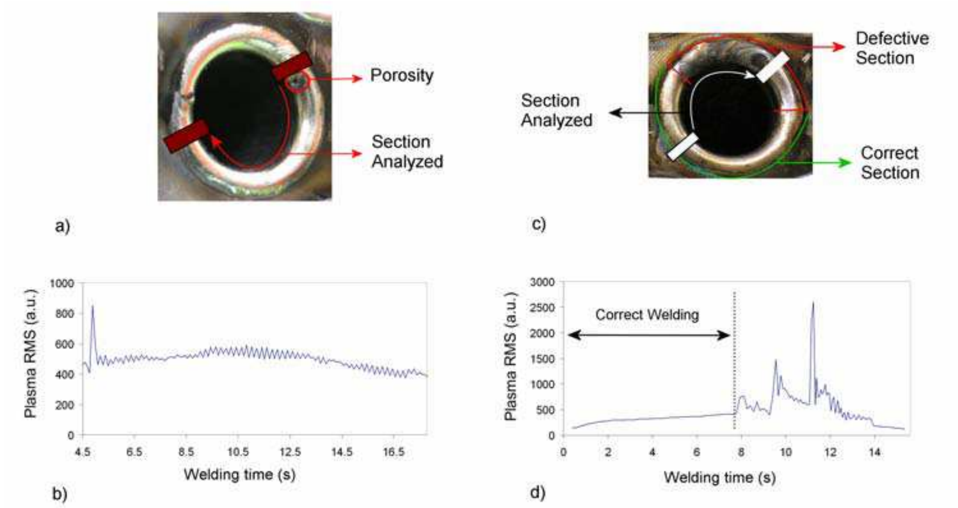


Fig. 14. The real-time calculation of the RMS value of the entire spectrum is able to detect some defects that other methods have trouble with

6. Conclusions and future works

An optical spectroscopic method for the monitoring of welding processes has been presented. It is based on the capture of the light emitted by thermal plasmas, which is characteristic of the arc and laser welding process. The spectroscopic analysis of the captured light provides rich information about the process behaviour, allowing to detect the occurrence of defects in the weld seam. Such a sensor system consists of an optical fibre to collect the light, a CCD spectrometer and a processing unit.

If the monitoring is to be performed in real-time, an important challenge for this approach is how to deal with the amount of generated data, because a typical scenario involves the capture of dozens of spectra per second, each one with thousands of spectral bands. For this reason, several spectroscopic processing techniques that try to optimize the real-time operation and defect-detection capabilities have been presented: an efficient computation of the electronic temperature profile, the analysis of the background radiation, the calculation of the RMS value of the spectrum, and the use of artificial neural networks (ANN) to automatically detect and classify defects from the captured spectra.

Those techniques have been validated in the manufacturing of large steam generators for nuclear power plants, in particular, the tube-to-tubesheet welding process. A solution for non-invasive capture of light in the orbital TIG welding process has been proposed, and the capabilities of each technique to detect typical defects in this process have been discussed. Up to some extend, all these method were able not only to detect defects but to discriminate between them, a capability much needed if the monitoring system is to be extended not only to monitor but to control the process. With this approach, some defects could be prevented in real-time.

The later represent the main research line for future works: the use of ANN and other techniques to improve the classification of defects in this application and the investigation of ways to control the welding process in real-time once a possible defect is being generated.

7. Acknowledgment

The authors want to thank to J.J. Valdiande, F. Linares and F. Gómez-Estefanía for their valuable contributions to this work.

8. References

Ancona, A.; Lugara, P.M.; Otonelli, F.; Catalano, I.M. (2004), A sensing torch for on-line monitoring of the gas tungsten arc welding process of steel pipes, *Meas. Sci. Tech.*, 15, 2412-2418, 0095-7023.

Ancona, A.; Spagnolo, V.; Lugara, P.M.; Ferrara, M. (2001), Optical sensor for real-time monitoring of CO2 laser welding process, *Applied Optics*, Vol. 40, N. 33, pp. 6019-6025, 0003-6935.

Bae, K.-Y.; Lee, T.-H.; Ahn, K.-C. (2002), An optical sensing system for seam tracking and weld pool control in gas metal arc welding of steel pipe, *Journal of Materials Processing Technology*, 120 (1-3), pp. 458-465, 0924-0136.

Bastiaans, G. J.; Mangold, R. A. (1985) The calculation of electron density and temperature in Ar spectroscopic plasmas from continuum and line spectra, *Spectrochim. Acta Part B Atomic Spectroscopy,* 40B 885-92, 0584-8547.

Bebiano, D.; Alfaro, S. C. A. (2009), A Weld Defects Detection System Based on a Spectrometer, *Seensor*, 9, 2851-2861, 1424-8220.

Cobo, A.; Mirapeix, J.; Conde, O.M.; García-Allende, P.B.; Madruga, F.J.; López-Higuera, J.M. (2007), Arc welding process control based on back face thermography: Application to the manufacturing of nuclear steam generators, *Proceedings of the of SPIE - The International Society for Optical Engineering, v 6541, 2007, Thermosense XXIX*, 0819466638, April, 2007, SPIE, Orlando (USA).

Cobo, A.; Mirapeix, J.; Linares, F.; Piney, J. A.; Solana, D.; López-Higuera, J. M. (2007a), Spectroscopic Sensor System for Quality Assurance of the Tube-To-Tubesheet Welding Process in Nuclear Steam Generators, *IEEE Sensors Journal*, Vol. 7, No. 9, pp. 1219-1224,

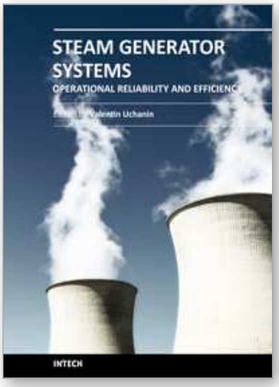
Dong, P. (2005) Residual stresses and distortions in welded structures: A perspective for engineering applications, Science and Technology of Welding and Joining, 10 (4), pp. 389-398, 1362-1718.

Ferri, F.; Pudil, P.; Hatef, M.; Kittler, J. (1994), *Comparative study of techniques for large-scale feature selection. Pattern Recognition in Practice IV: Multiple Paradigms, Comparative Studies, and Hybrid Systems*; Gelsema, E.S. (Ed.), Kananl, L.N. (Ed.), Eds.; Elsevier Science: New York, ISBN 0444818928, NY, USA.

García-Allende, P.B.; Mirapeix, J.; Conde, O.; Cobo, A.; López-Higuera, J.M. (2009), Defect detection in arc-welding processes by means of the line-to-continuum method and feature selection, *Sensors*, Vol. 9, No. 10, pp. 7753-7770, 1424-8220.

García-Allende, P.B.; Mirapeix, J.; Conde, O.; Cobo, A.; López-Higuera, J.M. (2008), Arc-welding quality assurance by means of embedded fiber sensor and spectral

processing combining feature selection and neural networks, *Sensors*, 8(10), 6496-6506, 1424-8220.
García-Allende, P.B.; Mirapeix, J.; Conde, O.; Cobo, A.; López-Higuera, J.M. (2009a), Spectral processing technique based on feature selection and artificial neural networks for arc-welding quality monitoring, *NDT&E International*, 42, 56-63, 0963-8695.
Griem, H. R. (1963), Validity of local thermal equilibrium in plasma spectroscopy, *Phys. Rev.*, Vol. 131, pp. 1170-6, 1050-2947.
Gu, H.; Duley, W.W. (1996), Statistical approach to acoustic monitoring of laser welding, *J Phys D*, 29 556-60, 0022-3727.
Li, L.; Brookfield, D.J.; Steen, W.M. (1996), Plasma charge sensor for in-process, non-contact monitoring of the laser welding process, *Measurement Science & Technology*, 7, pp. 615-26, 0957-0233.
Mirapeix, J.; Cobo, A.; Fernández, S.; Cardoso, R.; López-Higuera, J.M. (2008), Spectroscopic analysis of the plasma continuum radiation for on-line arc-welding defect detection, *Journal of Physics D: Applied Physics,* Vol. 41, No. 13, 0022-3727.
Mirapeix, J.; Cobo, A.; García-Allende, P.B.; Conde, O.; López-Higuera, J.M. (2010), Use of the plasma RMS signal for on-line welding quality monitoring, *Proceedings of the SPIE Photonics Europe*, Brussels, Belgium.
Mirapeix, J.; Cobo, A.; Quintela, A.; López-Higuera, J.M. (2007a) , Embedded spectroscopic fiber sensor for on-line arc-welding analysis, *Applied Optics*, Vol. 46, No. 16, pp. 3125-3220, 1559-128X.
Mirapeix, J.; García-Allende, P.B.; Cobo, A.; Conde, O.M.; López-Higuera, J.M. (2007), Real-time arc-welding defect detection and classification with principal component analysis and artificial neural networks, *NDT&E International*, 40, 315-323, 0963-8695.
Mirapeix, JM; Cobo, A.; Jaúregui, C.; López-Higuera, J.M. (2006), Fast algorithm for spectral processing with application to on-line welding quality assurance, *Meas. Sci. Technol.* 17 2623, 0095-7023.
Park, h.; Rhee, S.; Kim, D. (2001), Fuzzy pattern recognition based system for monitoring laser weld quality, *Measurement Science and Technology*, Vol. 12, N. 8, pp. 1318-1324, 0957-0233.
Poueyo-Verwaerde, A.; Fabbro, R.; Deshors, G.; De Frutos, A.M.; Orza, J.M. (1993), Experimental study of laser-induced plasma in welding conditions with continuous CO2, *Journal of Applied Physics*, 74 (9), pp. 5773-5780, 0021-8979.
Robinson, AW; Gardner, P; Stampfl, APJ; Martin R and Nyberg, G (1998), Error analysis in the fitting of photoemission lineshapes using the Levenberg-Marquardt method, *Journal of Electron Spectroscopy and Related Phenomena* 94 97-105, 0368-2048.
Wang, Y.; Zhao, P. (2001), Noncontact acoustic analysis monitoring of plasma arc welding, *International Journal of Pressure Vessels and Piping*, 78, 43-47, 0308-0161.
Wikle III, H.C.; Kottilingam, S.; Zee, R.H.; Chin, B.A. (2001), Infrared sensing techniques for penetration depth control of the submerged arc welding process, *Journal of Materials Processing Technology*, 113, 228-33, 0924-0136.
Workman Jr., J.; Springsteen, A.W. (1998) *Applied Spectroscopy: A compact reference for Practitioners*, London Academia Press Limited, ISBN 0127640703, London.
Wu, C.S.; Ushio M. & Tanaka M. (1997), Analysis of the TIG welding arc behaviour, *Computational Materials Science*, Vol. 7, pp. 308-14, 0927-0256.



Steam Generator Systems: Operational Reliability and Efficiency
Edited by Dr. Valentin Uchanin

ISBN 978-953-307-303-3
Hard cover, 424 pages
Publisher InTech
Published online 16, March, 2011
Published in print edition March, 2011

The book is intended for practical engineers, researchers, students and other people dealing with the reviewed problems. We hope that the presented book will be beneficial to all readers and initiate further inquiry and development with aspiration for better future. The authors from different countries all over the world (Germany, France, Italy, Japan, Slovenia, Indonesia, Belgium, Romania, Lithuania, Russia, Spain, Sweden, Korea and Ukraine) prepared chapters for this book. Such a broad geography indicates a high significance of considered subjects.