

Arc welding quality monitoring by means of near infrared imaging spectroscopy

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ABSTRACT

The search for an efficient on-line monitoring system focused on the real-time analysis of the welding quality is an active area of research, mainly due to the widespread use of both arc and laser welding processes in relevant industrial scenarios such as aeronautics or nuclear. In this work, an improvement in the performance of a previously designed monitor system is presented. This improvement is accomplished by the employment of a dual spatial-spectral technique, namely imaging spectroscopy. This technique allows the simultaneous determination of the optical spectrum components and the spatial location of an object in a surface. In this way, the spatially characterization of the plasma emitted during a tungsten inert gas (TIG) welding is performed. The main advantage of this technique is that the spectra of all the points in the line of vision are measured at the same time. Not only are all the spectra captured simultaneously, but they are also processed as a batch, allowing the investigation of the welding quality. Moreover, imaging spectroscopy provides the desired real-time operation. To simultaneously acquire the information of both domains, spectral and spatial, a passive Prism-Grating-Prism (PGP) device can be used.

In this paper the plasma spectra is captured during the welding test by means of a near infrared imaging spectroscopic system which consists of input optics, an imaging spectrograph and a monochrome camera. Technique features regarding on-line welding quality monitoring are discussed by means of several experimental welding tests.

Keywords: NIR imaging spectroscopy, plasma emission, arc-welding, on-line quality monitoring

1. INTRODUCTION

Several different approaches based on optical spectroscopy are used in a wide variety of monitoring scenarios. Ranging from environmental supervision [1] to food processing monitoring [2] or the fabrication of electronic components [3], the suitable analysis of the spectra acquired during the processes typically offer valuable and rich information. There are some particular scenarios where an optical spectroscopy approach seems especially suitable, as it happens when there is some light emission inherent to the process. In this case, optical emission spectroscopy can be used to analyze the information of the emitted spectra. A good example of this situation can be found in those applications where a plasma is generated during the process, like arc and laser welding. In fact, plasma optical spectroscopy has been proposed as a suitable technique for on-line weld quality monitoring.

Challenges lying in this framework are remarkable, as the physics involved in both arc and laser welding is quite complex [4]. In addition to this complexity, several external disturbances may affect the resulting quality provoking the appearance of defects in the seams. Depending on the specific application, these defects might give rise to serious consequences: a good example is the presence of a porosity in the seam of a tube in a nuclear power station steam generator [5]. The common approach to assure that the final welds are free of defects is the use of non-destructive evaluation techniques (NDT), such as penetrant liquids, magnetic particles or X-rays, in addition to test coupons where the optimal input parameters are determined. A reliable on-line monitoring system will be extremely useful in this regard, not only by its ability to provide real-time information about the process, but also because it could be used to prevent the appearance of flaws up to some extent.

It has been previously mentioned that plasma optical spectroscopy is a very promising monitoring solution for both arc and laser welding, and there are several works dealing with an efficient on-line spectroscopic analysis. The traditional approach is the calculation of the plasma electronic temperature T_e as the monitoring parameter, given that there is a known relation between T_e and the quality of the resulting seams [6,7,8]. Different proposals based on plasma optical spectroscopy have been also performed, like the use of Artificial Neural Networks (ANNs) to provide weld defect

classification [9], correlation analysis of the plasma spectra [10], or the use of synthetic spectra and optimization algorithms [11].

In this effort of exploring new alternatives, we propose in this paper the application of the technique known as imaging spectroscopy to the welding quality monitoring problem. Imaging spectroscopy is based on the simultaneous recording of both spectral and spatial information of a particular object or surface under analysis. This technique has proved to be especially suitable for airborne applications and industrial monitoring where real-time in-line inspection is desired. Examples of the latter can be found in the processing of tobacco [12] and food [13], or in biological applications [14]. In comparison with the traditional spectroscopic approach, where a single spectrum is recorded per sample, imaging spectroscopy provides several spectra associated with their spatial location through a given observation line, what can give rise to a more robust analysis. In addition, this technique is highly non-invasive, given that the hyperspectral device is attached to an industrial CCD-camera acquiring the spectral-spatial information.

2. IMAGING SPECTROSCOPY VERSUS PLASMA SPECTROSCOPY

2.1 Plasma optical spectroscopy

Spectroscopy can be defined as the measurement of the radiant intensity and energy of the interaction which takes place between light and any material. Rich information regarding the materials and compounds under analysis can be achieved by analysing the light absorbed or emitted in the process, given that the light-material interaction is highly dependent on the wavelength. Plasma optical spectroscopy can be defined as a variety within emission spectroscopy, where a suitable analysis of the plasma radiation may provide the desired data. Laser-induced breakdown spectroscopy (LIBS), for example, uses the energy provided by a laser source and focused on a given specimen to generate a plasma plume. The spectroscopic analysis of the plasma spectra can be employed to determine the chemical composition of the compound [15]. In this regard, when a plasma is generated in the context of an industrial process, as it happens with both arc and laser welding, plasma spectroscopy is a good solution to be used as a monitor system.

The key issue in terms of on-line welding quality monitoring is to determine, in real-time, when a defect has appeared. Obviously, the ideal approach would be, not only to offer information on defect appearance, but also to be able to prevent as much as possible those defects from happening. Although some different plasma diagnostics can be employed as monitoring parameters, the common approach is to estimate the plasma electronic temperature T_e , as it exhibits a direct correlation with the resulting weld quality. Several works have dealt with efficient implementations of this approach for both arc and laser welding quality monitoring [7,8]. A simplification of the Boltzmann-plot method [16] is typically used to provide the required T_e estimation

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

where E_m is the upper level energy, k the Boltzmann constant, I the relative intensity of the chosen emission lines, A the transition probability, g_m the statistical weight and λ the emission line central wavelength. The main benefit of using equation (1) lies in the reduced computational cost, as only two emission lines (of the same element in the same ionization stage) are involved in the calculations. However, the resulting T_e is typically less accurate than the one obtained via the Boltzmann-plot method, as several emission lines are considered in this case. An additional problem that may appear is related to the chosen emission lines, as an ambiguous identification would give rise to false alarms or undetected defects.

The immunity of fiber optic sensors to the strong electromagnetic interference inherent to arc-welding process is another relevant advantage of the traditional spectroscopic approach, although a key issue in this regard is the implementation of non-invasive input optics, allowing welding of complex structures and not interfering with the work of the operators. A typical arrangement of the input optics is based on the use of a collimator attached to an optical fiber [8]. In this sense, the plasma radiation is spatially integrated, and the resulting T_e is an averaged estimation. Input optics based on a fiber

sensor embedded within the arc-welding torch has been also proposed, exploiting the shielding gas flow to protect the fiber tip [17].

Detailed temperature maps can be also obtained by means of spatially resolved emission spectroscopy techniques [18], where a deconvolution process is typically carried out to provide the desired spatial resolution, like the Abel inversion. However, this approach can not be applied to on-line welding monitoring due to the high computational costs involved. It is worth noting that for arc-welding scenarios, it is typically assumed that the plasma is in Local Thermodynamic Equilibrium (LTE) [19], assuming that the plasma electron density is high enough so that collisional rates exceed the radiative ones. This also implies that different excitation temperatures can be found in terms of the plasma region analyzed. The condition to satisfy LTE can be expressed as

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

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

2.2 Imaging spectroscopy

As mentioned before, imaging spectroscopy can provide 2D images with spectral and spatial information along an observation line by using some hyperspectral device. In this paper we propose the use of an imaging spectrometer based on a passive prism-grating-prism (PGP) arrangement [20] attached to a monochrome CCD-camera. In this regard, it seems clear that the system can be highly non-invasive, as the camera and the imaging spectrometer can be located meters away from the welding torch, depending on the selected optics. In addition, the PGP device is immune to electromagnetic perturbations, which should not affect the CCD camera if it is conveniently protected.

A schematic representation of the images provided by the system is depicted in figure 1. Figure 1 (a) presents an image associated with the emission line of a laser with a central wavelength of λ_{laser} . It can be observed that the horizontal axis represents the spatial domain, while the vertical one is associated with the spectral information. A sample image of the plasma generated during an arc-welding experimental test is also depicted in figure 1 (b). While the whole plasma column is contained in the spatial axis, the plasma emission radiation has been recorded in the spectral window ranging from 400 to 1000 nm, approximately (λ_1 represents a higher wavelength than λ_2). The brighter lines indicate stronger spectral contributions, and the spectral resolution of the imaging spectrometer is 2.8 nm.

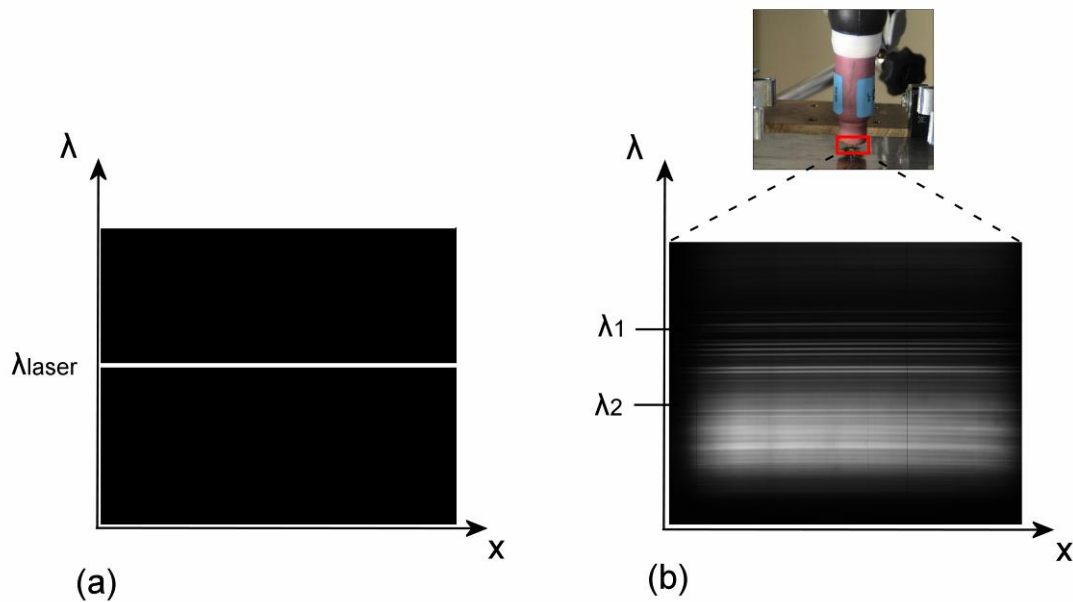


Figure 1. Examples of imaging spectroscopy: (a) image of a laser source; (b) image of welding plasma.

As suggested in figure 1 (b), the optics attached to the image spectrometer should be adjusted to cover the region of interest, in this case the plasma column which will be formed between the electrode tip and the plate. In this regard, an initial focus over the end of the gas nozzle should provide good results. To illustrate how the plasma radiation is formed during the welding process, figure 2 shows an image captured during a welding test in the laboratory. It can be appreciated that the radiation in the visible region is somewhat intense. To prevent the CCD sensor from a possible saturation a welding filter glass was used at the entrance of the selected optics.



Figure 2. Plasma radiation during arc-welding test.

3. EXPERIMENTAL SETUP

To validate the proposed approach based on imaging spectroscopy, the setup depicted in figure 3 was implemented. On the left side of the picture the imaging spectrograph (ImSpector V10E) can be observed attached to both CCD camera and the selected lens. As commented before, the chosen hyperspectral device covers a spectral range from 400 to 1000 nm using an on-axis optical configuration and a volume type holographic transmission grating in a prism-grating-prism (PGP) structure. The monochrome CCD-camera (Pixelink PL-A741 MV) is controlled by a computer via the IEEE1394 interface, and the lens attached at the end of the spectrograph is a Navitar Zoon 7000, whose zoom, aperture and focusing range are manually controlled.

The experimental tests were carried out with an arc-welding (Tungsten inert gas: TIG) system formed by a TIG power source (Kemppi Mastertig 2200), a welding torch (Kemppi TTC 220), and a positioning system (Newport MM4005 controller and two MTM100PP1 stage), where the plates are attached and controlled via PC. As suggested in figure 3, the welding torch, and therefore the plasma column, is kept fixed during the tests allowing the hyperspectral device to acquire the whole plasma radiation without variations in the capture conditions (i.e. focal distance, CCD integration time, etc.). The test seams were performed on AISI-314 stainless steel plates, and argon was used as shielding gas with a constant flow rate of 12L/min in standard operating conditions. The tip of the tungsten electrode (1mm thickness) was placed at approximately 1 mm away from the plates.

An optical fiber (Ocean Optics P50-2-UVVIS) can be also appreciated on the right side of the picture. One end of the fiber (2 meters length, 50 μm core diameter) was focused on the plasma axis (between the electrode tip and the plate) and the other was attached to CCD spectrometer (Ocean Optics USB2000). The distance between the fiber end and the plasma axis was approximately 14 cm. The purpose of this additional setup is to check the validity of the new proposal by establishing a correlation between the hyperspectral analysis and the traditional spectroscopic solution.

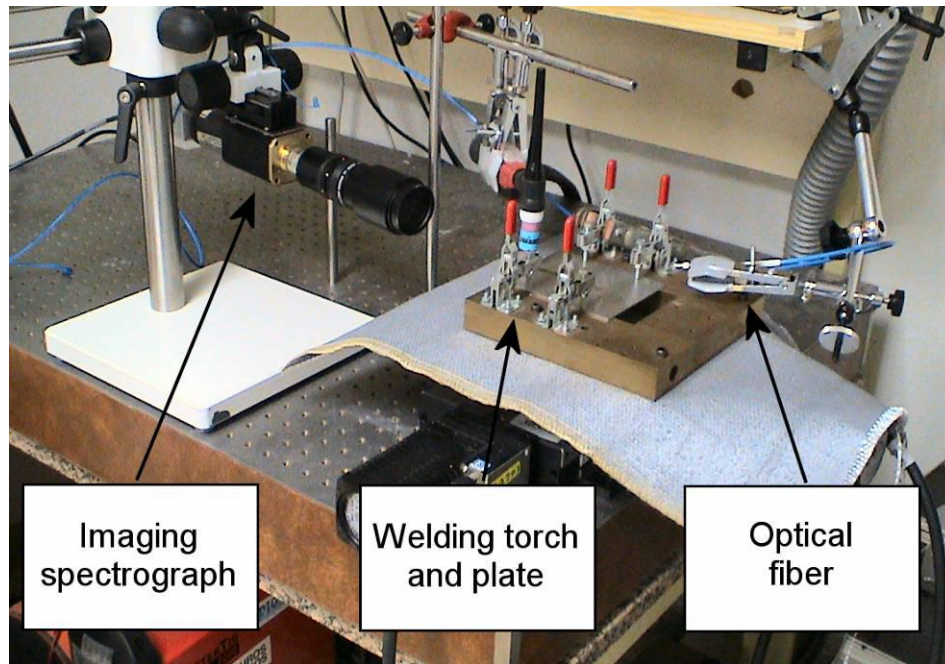


Figure 3. Experimental setup.

4. EXPERIMENTAL ISSUES

An initial adjustment of the lens attached to the imaging spectrometer was carried out to obtain a maximum spatial resolution on the plasma column, thus exploiting the benefits of imaging spectroscopy applied to on-line welding quality monitoring. In this regard, the distance between the lens end and the welding torch was minimized as much as possible, resulting in a final separation of approximately 13 cm. As mentioned above, a welding filter glass had to be used to prevent the CCD camera from saturation due to the intense plasma radiation.

Several experimental tests were performed to analyze the acquired hyperspectral images. Frames obtained during tests with constant welding currents of 26, 42 and 50 A are depicted in figure 4 (a), (c) and (d), respectively. As expected, for higher welding currents there is a stronger spectral contribution through the whole range under analysis. In addition, several individual emission lines are resolvable and could be use to develop a spectroscopic study. The associated spectra obtained via the optical fiber and the CCD spectrometer are also presented in figures 4 (b), (d) and (f). It should be mentioned that integration times are different for the spectra depicted in figures 4 (b) and (d) (40 ms), and 5 (f) (20 ms). It is also interesting to mention that, although there is a certain level of saturation in figure 4 (e), particularly in the area associated with the plasma center in the visible region, a spectroscopic analysis will be feasible by using spectra at different spatial locations.

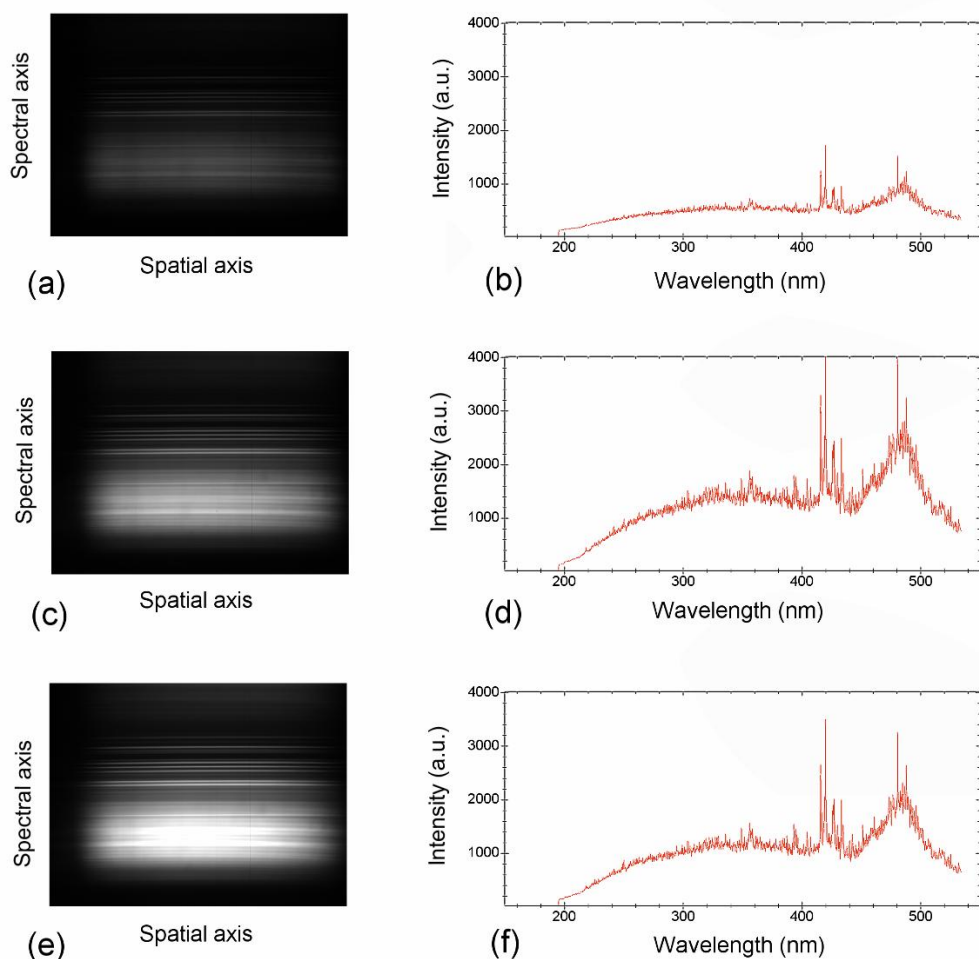


Figure 4. Welding tests with different constant welding currents: (a) and (b) welding current of 26 A and spectrometer integration time of 40 ms; (c) and (d) welding current of 42 A and spectrometer integration time of 40 ms; welding current of 50 A and spectrometer integration time of 20 ms.

Images regarding the analysis of a seam performed in a plate with an incision orthogonal to the weld direction are also shown in figure 5. In this case the welding current was kept fixed at 46 A, and the ability of the system to identify a variation in the plate width was checked. The plate initial width is 1.5 mm, and the incision diminishes it to 1 mm. Figures 5 (a) and (c) presents hyperspectral images captured just before and after the plate incision. A particular region of interest (ROI) has been chosen to highlight the variation in the contribution of a specific plasma emission line. While in the images mentioned above this line exhibits a clear intensity, in figure 5 (b), which is associated with the lesser width, its contribution disappears. Consequently, this line could be used to carry out an image processing over a reduced region of interest, thus saving computational times. This has been carried out in the simple analysis presented in figure 6. The front and back face of the seam with the orthogonal incision can be observed in figures 6 (a) and (b). The resulting monitoring signal has been obtained by defining a ROI similar to the one chosen in figure 5 and extracting the intensity plane of the resulting picture. The quantification of the average intensity gives rise to the profile exhibited in figure 6 (c).

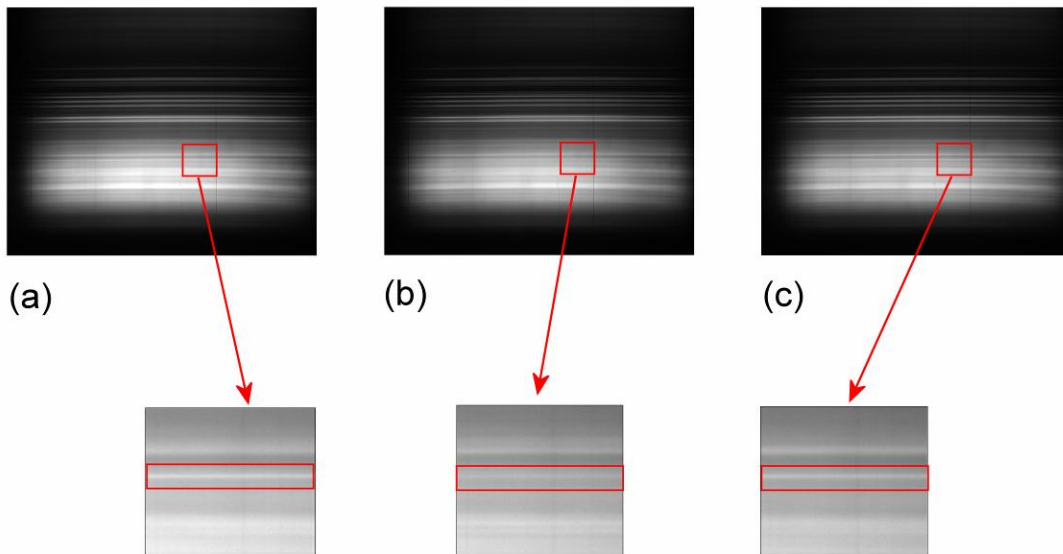


Figure 5. Analysis of a seam with width variations: (a) plate width of 1.5 mm; (b) plate width of 1 mm; (c) plate width of 1.5 mm.

A different kind of weld defect was simulated via a perturbation on the shielding gas flow rate. The purpose of the shielding gas (argon in our case) in arc-welding process is to prevent the appearance of oxidation in the seams. For this reason, it is highly interesting to detect whether the gas flow rate is kept constant through the process. The hyperspectral images presented in figure 7 correspond to a seam performed with a constant welding current of 37 A, and an initial argon flow rate of 12 L/min. The gas flux was manually altered, shortening it to approximately 2 L/min during 0.5 s. This action was repeated twice during the whole seam, and the images associated with this gas reduction are depicted in figures 7 (b) and (d). The difference between these frames and the ones shown in figures 7 (a), (c) and (e), associated with “correct” welding conditions, can be clearly appreciated.

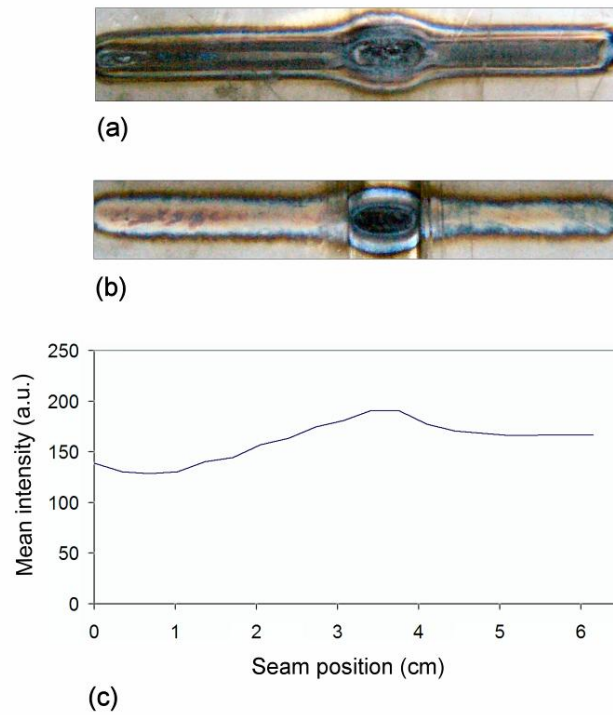


Figure 6. Simple monitoring approach for a seam with width variations: (a) seam with incision (front face); (b) seam with incision (back face); (c) image processing for defect detection.

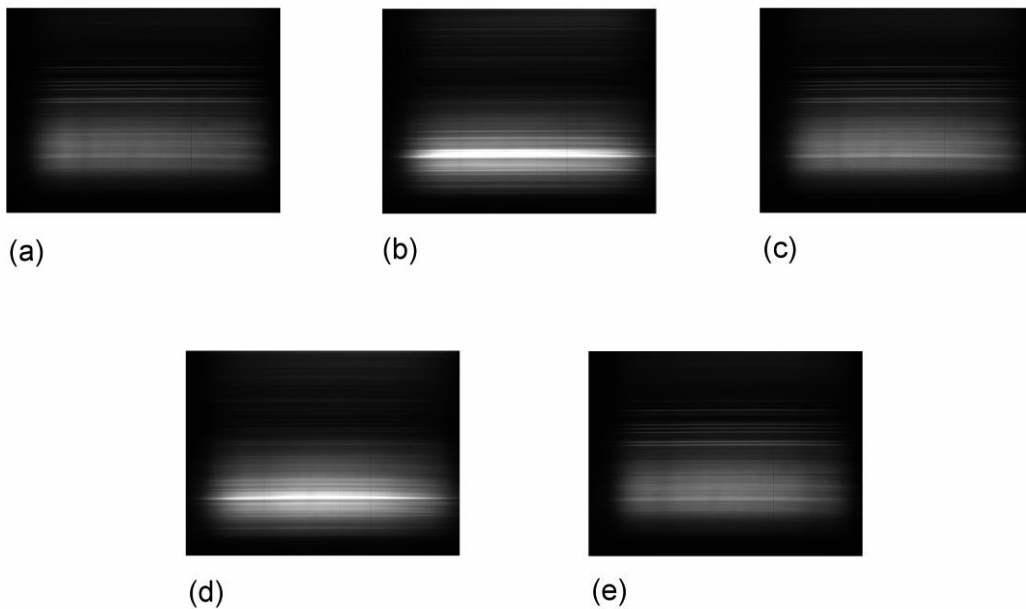
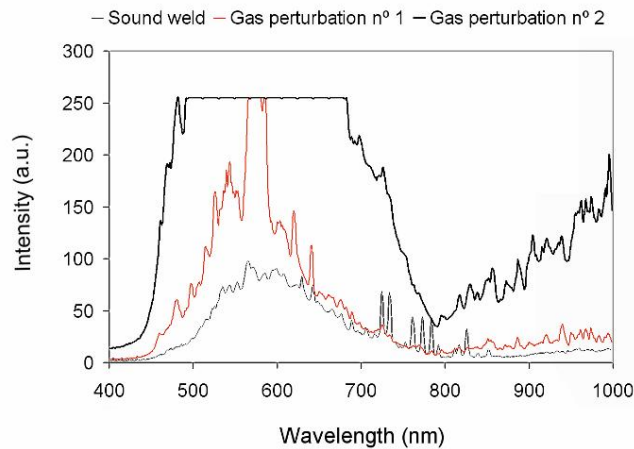
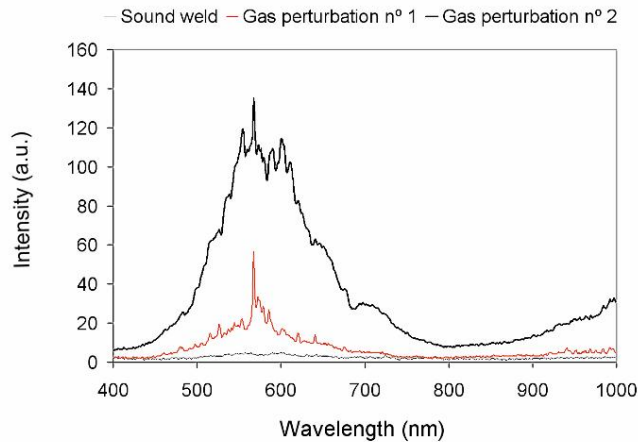


Figure 7. Images of welding process with perturbations on the gas flow rate: (a), (c) and (e) gas flow rate of 12 L/min; (b) and (d) gas flow perturbation (2 L/min).

As discussed above, one of the main benefits that can provide imaging spectroscopy applied to on-line welding monitoring is the additional value that comes out from the spatial information. A good example to illustrate this advantage is the study introduced in figure 8. For the weld test already presented in figure 7, the plasma spectra for different spatial locations have been analyzed. The average of the pixels 256 to 260 associated with the spatial axis is depicted in figure 8 (a) for three different welding times: normal operating conditions (sound weld) and two shielding gas flow reductions (gas flow perturbations n° 1 and 2). It is worth remembering that the resolution of the chosen CCD-camera is 640x480 pixels, being the former the one selected to provide the spatial resolution. In this regard, the pixel numbers 256 to 260 are associated with a spatial region in the vicinity of the plasma axis. It can be appreciated how the averaged spectrum referring to the second gas perturbation provides a saturation in the intensity in the spectral window from 490 to 680 nm, approximately. Figure 8 (b) presents the same analysis for pixel numbers 636 to 640, i.e. associated with the outer part of the plasma column. The results in this case suggest that the spectral band located at $\lambda = 567.5$ nm is sensitive to the simulated welding perturbation.



(a) Average from pixels 256 to 260



(b) Average from pixels 636 to 640

Figure 8. Spatial analysis of the plasma radiation for experimental test: (a) average from pixels 256 to 260; (b) average from pixels 636 to 640.

5. RESULTS AND DISCUSSION

In this paper we have explored the possibility of applying imaging spectroscopy to on-line weld quality monitoring. The ability of hyperspectral devices such as PGP-based imaging spectrographs to provide 2D images with both spectral and spatial information can be exploited to extract relevant information from the plasma radiation. In comparison with the traditional spectroscopic approach, where the spectra are recorded by means of a spatial integration through the plasma column, imaging spectroscopy enables to carry out a detailed analysis in different plasma regions, thus enriching the spectroscopic approach. It is worth mentioning that the proposed solution is highly non-invasive, given that it is based on a CCD-camera attached to the imaging spectrograph, which could be placed faraway from the welding process.

Arc-welding experimental tests have been developed in the laboratory to check the validity of the technique. Analyses have been conducted on seams where different welding currents have been employed; plates with width variations have been also included in the studies and perturbations on the shielding gas flow have been manually performed. It has been demonstrated that the images offered by the designed system can be used for monitoring purposes. In this regard an extremely simple image processing approach has been used to deliver a suitable monitoring parameter able to detect variations in the plate widths. Finally, it has been shown that a detailed spatial analysis of the plasma spectra may give rise to an optimal selection of the spectral bands to take part into the monitoring process.

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