Non-Invasive Spectroscopic System for Non-Destructive Arc-Welding Analysis

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Abstract. In welding processes, specially in those involved in critical applications, as the aerospace an automotive sectors, extensive non-destructive testing (NDT) is commonly used for quality assurance. Therefore, the possibility of avoiding those procedures by means of on-line, real-time monitoring techniques is of high interest.

Several different approaches have been contemplated for the analysis of welding processes, from the measurement of the charge voltage induced by the plasma on the welding nozzle, to acoustic and imaging techniques. Spectroscopic analysis of the plasma emission spectrum is known to offer rich information about the process, allowing direct correlation between the weld quality and some plasma parameters.

Despite its benefits, spectroscopic analysis exhibits the drawbacks of its high computational requirements and the difficulty of a non-invasive arrangement of the optical light-capturing system. In a previous paper a new spectroscopic technique allowing real-time full-spectroscopic analysis of arc welding processes, and, hence, detection of common defects in the weld seam, was presented. In this paper a welding monitoring sensor system in which the optical fiber capturing the light is embedded into the welding torch is presented. Several tests showing the feasibility of the proposed system are also presented.

1. Introduction

Although arc and laser welding are manufacturing processes that have been widely used for years, their introduction in the nuclear, aerospace and automotive sectors, among others, has led to an increase in research concerning quality assurance of these welding techniques. The inherent complexity of these processes has made impossible to find a generic theoretical model able to provide mathematical formulation to determine appropriate welding parameters for given conditions. Although procedure trials are employed to try to cope with this lack of knowledge, the influence of several disturbances, which may appear during the welding process, can also affect the resulting weld quality.

The use of off-line, non-destructive testing techniques (x-rays, penetrant liquids, magnetic particles, ultrasonics, etc.) is a common practice to identify defective welds. As these techniques are time-consuming and expensive, a reliable alternative would be of great interest. The benefits of an on-line sensing and control system would be, not only to monitor the process on-line, but also to mitigate or even prevent possible defects from happening. This would reduce costs and improve productivity.

Several different techniques have been proposed to sense and control welding processes, from analyzing the electrical [1], or acoustic emissions [2] produced during the welding process, to image processing by means of infrared thermography [3]. However, the development of an optimal on-line sensor and control system is still an active area of research. Plasma spectroscopy is an interesting alternative, as it has been demonstrated that the plasma radiation in the ultraviolet and visible bands can be correlated with some parameters of the resulting welds [4-5]. The inherent immunity of optical systems to electromagnetic interferences (EMI), which can be a serious problem for the electrical and acoustic solutions, and the wide variety of possible optical sensor setups (remote photodiodes [6] and optical fiber capturing [7]) are some of the advantages of optical methods.

Despite the diversity regarding input optics alternatives, the arrangement of optical devices such as collimators in the vicinity of the welding torch can be a drawback in terms of invasiveness. On the other hand, in particular welding scenarios, like processes in which complex shapes are involved, the solution to the input optics arrangement is not trivial. In addition, problems such as heating or pollution interference in the input optics must be also taken into consideration.

In this paper, a new solution to the problem of capturing the plasma light radiation during arc welding process is presented. An optical fiber embedded into a TIG torch is used as the optical sensor of an arc-welding quality assurance technique based on plasma spectroscopy. Several tests performed in the laboratory will show the feasibility of the proposed system.

2. Plasma spectroscopy

It has been demonstrated that the quality of a weld exhibits a correlation with the events to be found in its associated plasma electronic temperature T_e profile. The plasma electronic temperature can be determined by using the Boltzmann equation [8], which allows to find the population of an excited level by means of the following expression:

$$N_m = \frac{N}{Z} g_m \exp\left(\frac{-E_m}{\kappa T_e} \right), \tag{1}$$

where N is the population density of the state m, Z the partition function, g_m the statistical weight, E_m the excitation energy, κ the Boltzmann constant and T_e the plasma electronic temperature. Several emission lines of the same atomic species in the same ionization stage are used as the input date for Equation (1), what enables different T_e estimations depending on the atomic species participating in the plasma. Equation (1) can be used when the plasma is in local thermal equilibrium (LTE), condition that is assumed to be valid when

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

where N_e is the electronic density and ΔE is the largest energy gap in the atomic energy level system. In addition, in optically thin plasmas, the intensity of a given emission line I_{mn}, induced by a transition from the level m to the level n, can be related to the population density of the upper level N_m through

$$I_{mn} = N_m A_{mn} h \gamma_{mn}, \tag{3}$$

where A_{mn} is the transition probability, and $h\gamma_m$ the energy of that transition.

When equations (1) and (3) are combined, T_e can be obtained from the following expression

$$\ln\left(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}\right) = \ln\left(\frac{hcN}{Z}\right) - \frac{E_m}{kT_e} . \quad (4)$$

It can be seen that T_e can be calculated with equation (4), as the plot resulting from using various lines from the same atomic species in the same ionization state and representing the left-hand side of equation (4) versus E_m has a slope inversely proportional to T_e. This technique is known as Boltzmann-plot.

3. Experimental issues.

Traditionally, the input optics of the systems designed to capture the light coming from the plasma generated during an arc welding process are formed by a collimator attached to an optical fiber. The optical fiber guides the light radiation to a spectrometer, where a spectrum of the plasma can be obtained. However, as it was mentioned in Section 1, these solutions tends to be invasive, an in some particular cases can not even be considered due to the specific conditions of the welding processes. Some systems where the input optics is attached to the welding torch have been proposed [7], but in some cases it can also be a drawback in terms of disturbances to the human operator or adaptability to an industrial environment.

Arc-welding processes exhibit physical properties which are extremely aggressive to almost any kind of sensor placed at just centimetres away from the electrode tip. However, the use of one of the welding nozzle shielding gas exits to guide the fiber allows to avoid the very high temperatures inherent to the process, as the shielding gas has a cooling effect upon the fiber. In addition, the shielding gas flux keeps possible projections from colliding with the fiber tip, or from interfering in the light capture. In Figure 1, a scheme of the options mentioned above is presented. In Figure 1 (a) an scheme of the optical inputs arrangement when considering the use of a collimator is depicted. The collimator must be focused to the axis formed within the electrode tip and the plate to capture the plasma radiation. In Figure 1 (b) an image of the optical fiber embedded within the TIG torch is shown. The ceramic protection of the torch has been removed to observe the fiber.

In this case the fiber, a P50-UVVIS (Ocean Optics) of 50 µm core diameter and one meter length, is guided through the torch and attached to a 2048-pixel CCD spectrometer (Ocean Optics USB2000). To check the resistance of the fiber to the welding process 50 different tests were performed, with welding currents up to 70 A and a shielding gas (Ar) flow rate of 12 L/min. The embedded fiber arrangement is the one depicted in Figure 1(b), and during the welding tests the electrode tip was placed at approximately 2 mm from the plate. One additional concern is related to the possibility that intense radiation in the UV region may introduce wavelength-dependent optical losses in the optical fiber. This phenomenon, commonly referred to as solarization, is believed to be associated with the formation of color centers [9]. In order to check the spectral response of the fiber used in our experiments, its transmission spectrum was recorded before and after its exposition to the plasma radiation. In Figure 2 a comparison between these spectral responses is presented.

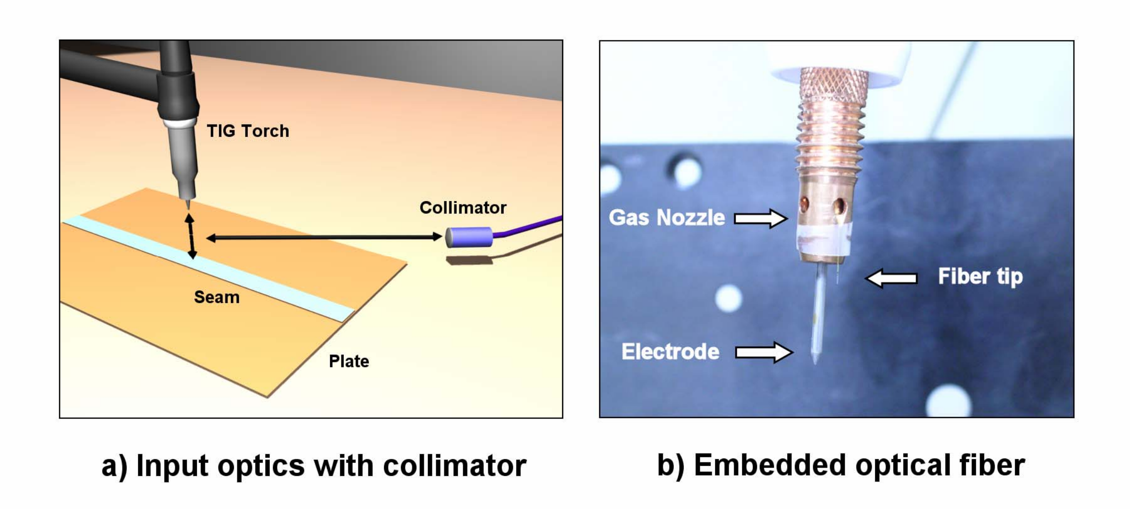


Figure 1. Input optics with collimator scheme and image of the fiber embedded into the TIG torch.

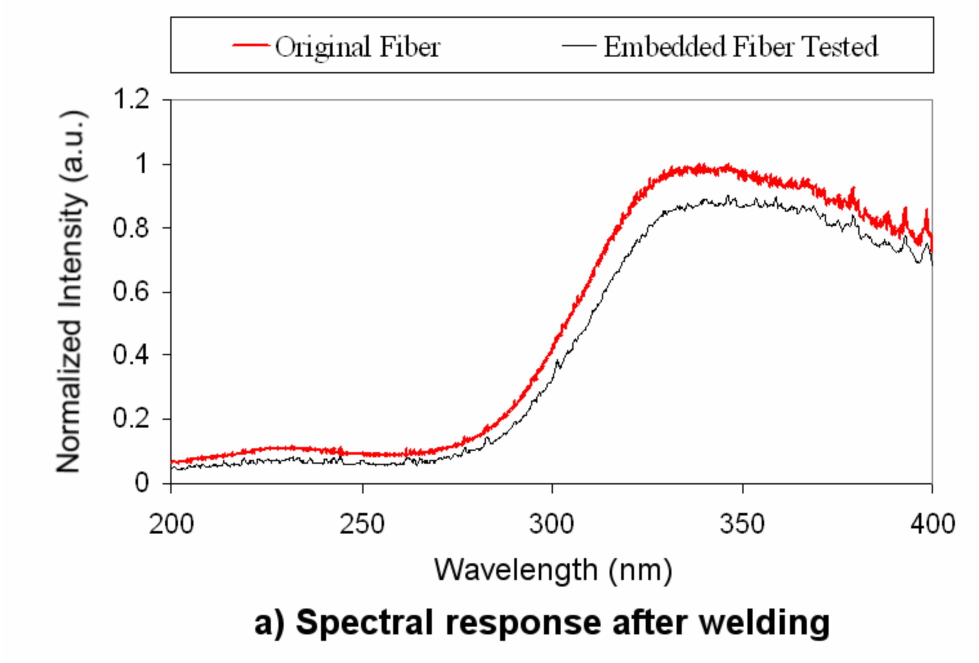


Figure 2. Spectral response of the fiber before and after extensive welding tests.

A DH-2000 Deuterium Tungsten light source was used to obtain the data depicted in Figure 2. The Deuterium source was selected, as it provides enough light between 200 and 400 nm. In addition, another 2 meter length optical fiber identical to the one embedded into the torch was employed as a reference. It is worth noting that the amount of light captured by the fibers is of no relevance here, as this parameter will depend on the cut performed to the fiber tip. It can be seen that, in terms of spectral response, the fiber embedded into the TIG torch does not exhibit any clear deterioration in its transmission spectrum, as both spectra shown in Figure 2 are almost identical.

4. Results

A comparison of the plasma spectra captured during welding processes is presented in Figure 3. In Figure 3 (a) a spectrum, recorded by using a collimator and optical fiber as input optics, is depicted. The result obtained when the sensor system formed by the embedded optical fiber is used is shown in Figure 3 (b). In both figures the mean value of the spectrum in each point, calculated with a smoothing algorithm considering 40 samples per wavelength, is also displayed. The response of both systems for wavelengths higher than 350 nm is almost identical, implying again that no wavelength-dependent losses seem to be introduced in the fiber due to the plasma radiation. In the case of the embedded fiber, spectral information also appears for wavelengths inferior to 350 nm. The reason to this effect is to be found in the smaller length of the fiber embedded in the welding torch (1 meter) in comparison to the one used to guide the light from the collimator to the spectrometer (2 meters).

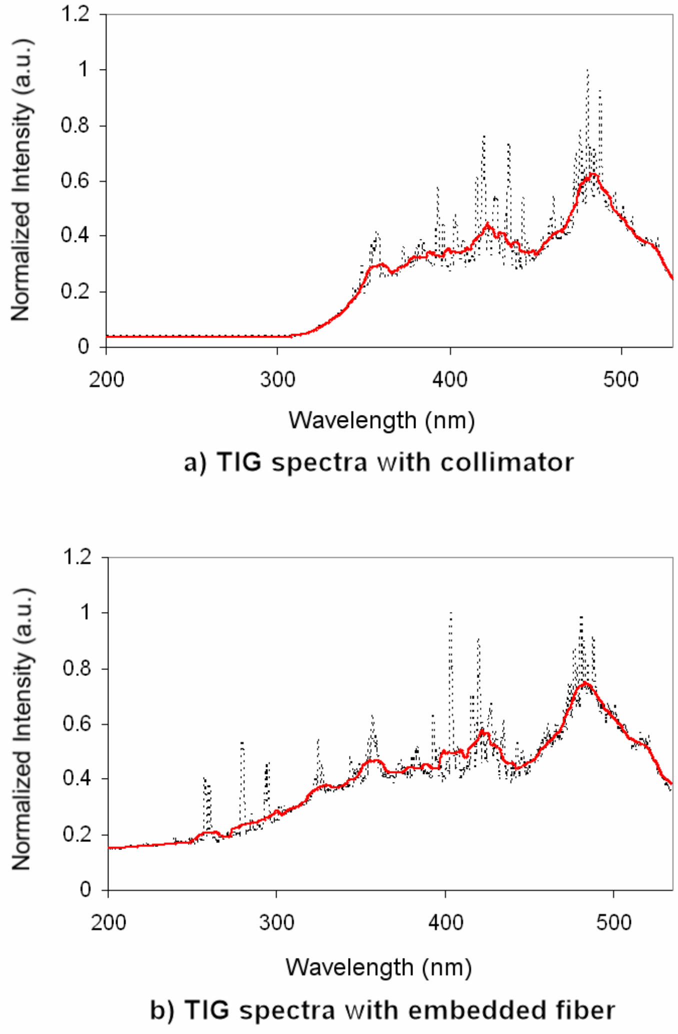
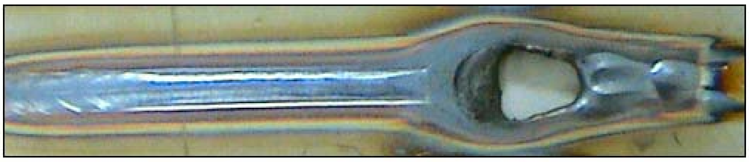
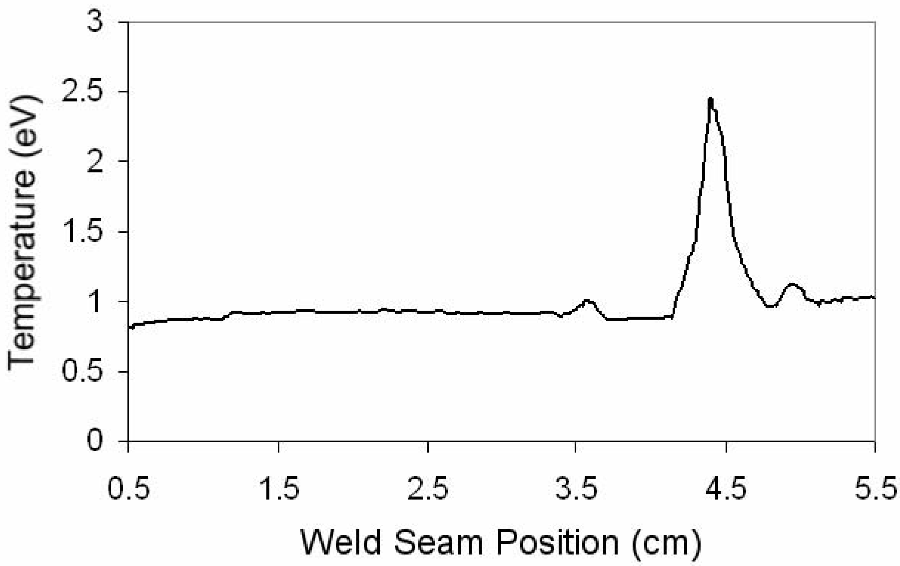


Figure 3. Spectra captured with collimator and embedded fiber.

An example of the feasibility of the sensor to be integrated within a welding quality assurance system is shown in Figure 4, where a weld with a clear defect is presented. The defect was provoked by an incision performed in the plate, orthogonal to the weld direction, provoking a discontinuity in the plate width from 2 to 1 mm.



a) Defective Weld



b) *Te* profile

Figure 4. Example of weld defect detection by means of the embedded fiber and plasma spectroscopy.

The welding current employed in the tests was 65 A, and the Ar flow rate 12 L/min. A T_e profile, calculated by employing Equation (4) with 7 Ar II lines located from 459 to 489 nm, is depicted in Figure 4 (b). It can be seen that fluctuations in the T_e profile appear in the area where the crater is formed, giving T_e values away from the ones obtained when a sound weld is obtained (approximately 0.85 eV).

5. Conclusions

A new non-invasive spectroscopic sensor disposition for non-destructive arc-welding quality analysis has been presented in this paper. By using one of the shielding gas nozzle exits within a TIG welding torch, an optical fiber can be embedded into the torch and used to capture the light radiation from the plasma formed during the welding process. It has been demonstrated, with several welding tests, that no wavelength-dependent losses appear in the fiber after welding. The shielding gas cooling effect upon the fiber avoids physical deterioration of the fiber tip. In addition, it has been shown that not only plasma spectrum are obtained, but also welding quality analysis is feasible when using the embedded sensor as input optics of the plasma spectroscopy system.

6. References

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