

Spectroscopic Polymer Optical Fiber sensor for orbital arc-welding on-line monitoring

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ABSTRACT:

Plasma optical spectroscopy has proved to be a promising solution for the on-line monitoring of both laser and arc-welding processes, where quality assurance plays a mayor role, especially in some particular industrial scenarios like aeronautics. Despite the robustness provided by these spectroscopic analysis techniques, the implementation of an efficient and non-invasive optical sensor system is not always feasible. Input optics based on optical collimators are commonly employed, but when complex shapes are to be welded, or specific welding processes are being considered, a different approach must be designed.

In this paper we propose an optical sensor based on the use of a Polymer Optical Fiber (POF) as the input optics. The external protection of the POF is removed, providing an acquisition of the plasma radiation from the fiber cladding. Experimental welding tests will show the feasibility of the proposed POF sensor.

Key words: Polymer Optical Fiber, fiber sensor, plasma optical spectroscopy, arc-welding, on-line monitoring.

1.- Introduction

On-line weld quality monitoring is currently an active area of research, given that in some significant industrial sectors (e.g. aeronautics, nuclear) the assurance of the weld quality plays a mayor role. Although several on-line monitoring systems based on different approaches have been proposed [1][2], both procedure trials and Non-Destructive Evaluation Techniques (NDT) are typically employed to assure the absence of the defects in the seams. In this regard, plasma optical spectroscopy has attracted some attention, as its implementation as an on-line weld quality monitoring system offers some relevant advantages, like the immunity of optical sensors to the Electromagnetic Interference (EMI), or the robust analysis provided by the study of the plasma spectra. The traditional spectroscopic approach for weld quality monitoring lies in the estimation of the

plasma electronic temperature T_e , as there is a correlation between this parameter and the resulting weld quality [3]. In addition, it has been demonstrated that real-time analysis can be provided [4], and some new analysis techniques have been proposed [5,6].

Although the common use of optical collimators focused on the plasma axis is suitable for some scenarios [7], there are situations where a specific optical sensor has to be designed. In the robotic welding of complex shapes, for example, the arrangement of the collimator, external to the welding torch, can be a serious drawback. The particular problem under analysis in this paper is the orbital arc-welding process used for the fabrication of steam generators for nuclear plants. As it will be shown, arrangements based on the use of both collimators or cosine correctors are not feasible in this case, as the weld head axis

prevents enough plasma radiation from being captured during an interval of the process.

A POF sensor has been proposed to avoid this problem. By removing the external fiber jacket and winding the fiber within the internal side of the welding head, the whole fiber length will work as the system input optics. By means of several experimental welding tests it will be demonstrated that plasma spectroscopic analysis is feasible with the proposed fiber sensor.

2.- Plasma optical spectroscopy

The estimation of the plasma electronic temperature T_e can be fulfilled by several techniques. However, when a real-time analysis is needed, the following equation is typically considered:

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

where E_m is the upper level energy, k the Boltzmann constant, I the emission line intensity, A the transition probability, g_m the statistical weight and λ wavelength associated with the transition.

Equation (1) is a simplification of the so-called Boltzmann-plot:

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

where h is the Planck constant, c the light velocity, N_m the population density of state m , and Z_m the partition function. It is worth noting that in the case of Equation (1) only two emission lines (from the same element in the same ionization stage) are involved in the estimation of T_e . Equation (2) provides a more stable T_e profile by representing the left-hand side versus E_m , given that the slope of the resulting plot is inversely proportional to T_e . Several emission lines can be considered in this case. Equation (2) is derived from the Boltzmann Equation [8], and the expression allowing the determination of the intensity of a given emission line:

$$I_{mn} = N_m A_{mn} h \gamma_{mn}, \quad (3)$$

where γ_{mn} is the optical frequency.

3.- Experimental issues

3.1.- Welding process scenario

Enough plasma radiation has to be captured during the welding process to allow the calculation of T_e . To illustrate the particular welding scenario, a schematic representation of the automatic orbital weld head (*Arc Machines Inc.* Model 96) is presented in Fig. 1.

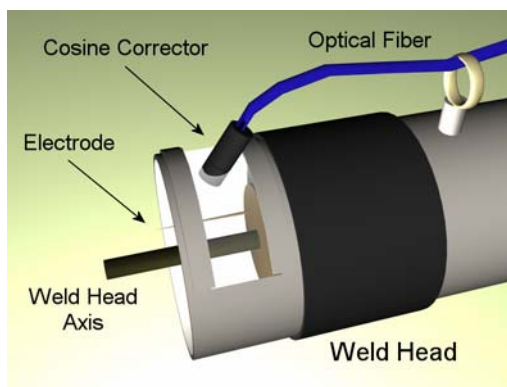


Fig. 1: Schematic representation of the welding head with input optics based on cosine corrector and optical fiber.

The weld head axis is used to anchor the head to the tube to be welded. The tungsten electrode rotates around the axis to complete each tube seam. On the top of the weld head a polycarbonate window allows the operator to visually supervise the process.

An initial fiber-based optical sensor design can be observed in Fig. 1. The input optics is composed of a cosine corrector (Ocean Optics CC-3-UV) and a silica optical fiber (600 μm core diameter), which delivers the collected radiation to a CCD spectrometer (Ocean Optics USB2000). The use of the cosine corrector allows the acquisition of the welding plasma radiation over 180°. This sensor system facilitates a proper spectroscopic analysis for approximately 90% of the welding process. As mentioned above, when the weld head axis occludes the electrode from the “line of sight” of the cosine corrector, the amount of light is not enough as to perform the required T_e computation, even if the integration time in the spectrometer is maximized.

An example of this problem is shown in Fig. 2, where a T_e profile is depicted. The computation of the plasma temperature was carried

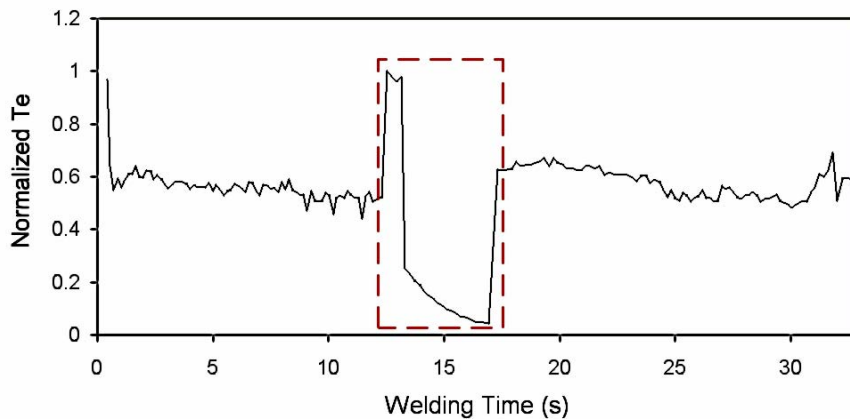


Fig.2: T_e profile with a "shadow region" where a correct analysis is not feasible .

out by means of Eq. 1 and two Mn emission lines, with central wavelengths at approximately 358 and 403 nm (the spectral range of the spectrometer covers from 190 to 535 nm).

The "shadow region", where there is not enough plasma radiation to correctly estimate T_e (normalized according to its maximum), has been highlighted in Fig. 2. This problem has to be solved, as some weld defects could be produced within this "shadow region", where they can not be identified by this spectroscopic approach.

3.2.- POF sensor design

As previously mentioned, the proposed new sensor is based on a POF cable, where the external jacket has been removed. One end of the cable has a SMA connector to be attached to the spectrometer, while the other one was cut. Figure 3 depicts the POF cable wound within the external section of the weld head.



Fig.3: POF cable wound within the external section of the weld head.

It can be seen that an adhesive thermal tape has been used to protect the POF cable from the heating of the weld head.

3.2.- Experimental validation

Several welding tests were performed in the laboratory to check the validity of the proposed sensor. A TIG (Tungsten Inert Gas) arc-welding system was used in these experiments. It was composed of a TIG power source (Kemppi Mastertig 2200) and a TIG torch (Kemppi TTC 220). The plates (AISI 304 stainless-steel) were fastened to a high-precision positioning system formed by the controller (Newport MM4005) and two linear stages (Newport MTM100PP1), with a resolution of $1 \mu\text{m}$ in both axes. The whole system is controlled by a desktop PC, which also performs the real-time analysis. The system is able to perform both linear and circular seams. An image of the experimental setup is depicted in Fig. 4.

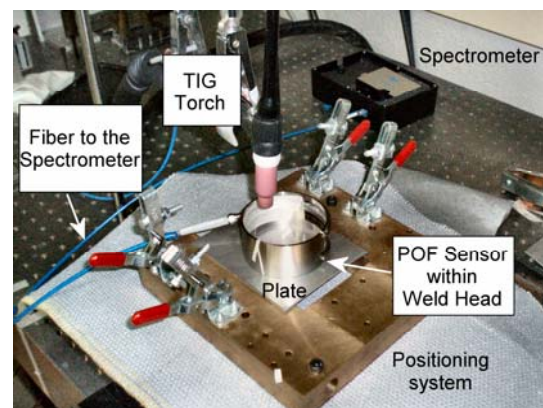


Fig.4: TIG arc-welding experimental setup.

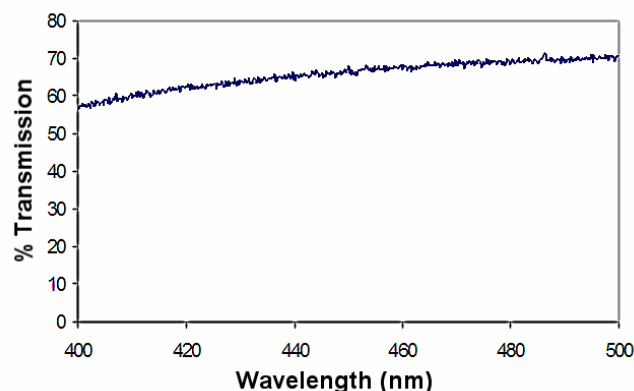


Fig.5: POF cable transmission spectrum.

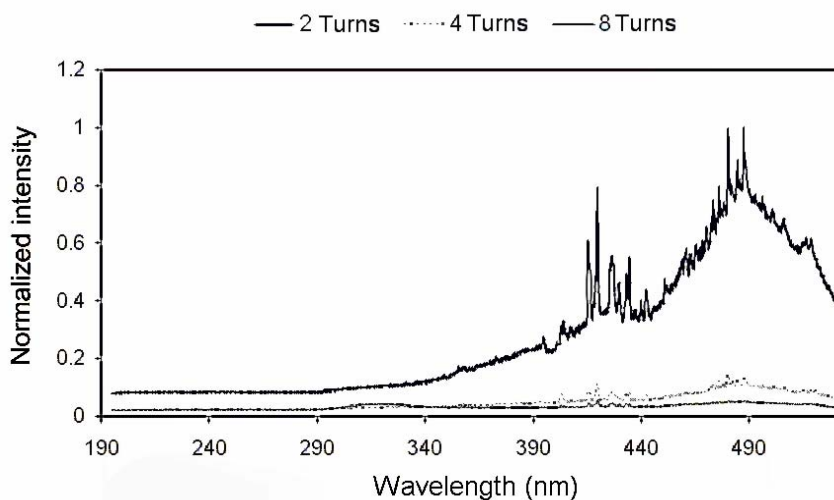


Fig.6: Plasma spectra captured by means of POF sensor.

It is worth noting that an additional silica fiber (core diameter 600 μm ; length 2 m) is used to deliver the captured radiation to the spectrometer. The spectral response (in transmission; see Fig. 5) of the POF cable (2 meter length) was characterized using a DH-2000 (Ocean Optics) white-light source. It can be appreciated that the response is almost constant in the spectral range analyzed.

Once the spectral response of the fiber is known, several welding tests were performed to validate the sensor proposal. In Fig. 6 plasma spectra for different sensor lengths are presented. During the experiments, argon was used as shielding gas with a constant flow rate of 12 L/min. A constant welding current of 50 A was also employed. As expected, the amount of light collected by the input optics increases as the length (number of turns) of the POF cable also increases.

For 8 turns, the total length of the POF cable is 176 cm; for 4 turns 88 cm and 44 cm for 2 turns. It can be appreciated that the POF cable exhibits a great attenuation for wavelength lower than 350 nm. However, in the spectral region between 400 and 500 nm there is enough emission lines as to perform a complete spectroscopic analysis.

3.2.- Field tests

The proposed sensor system was checked in the facilities of ENSA (Equipos Nucleares S.A.) in Maliaño, Spain. Several tests were carried out during the tube-to-tubesheet welding process in a steam generator. More than 20 seams were performed (with an approximate total welding time of 640 seconds), and the POF cable did not show any deterioration in its transmission spectral response. An example of a plasma spectrum is presented in Fig. 7.

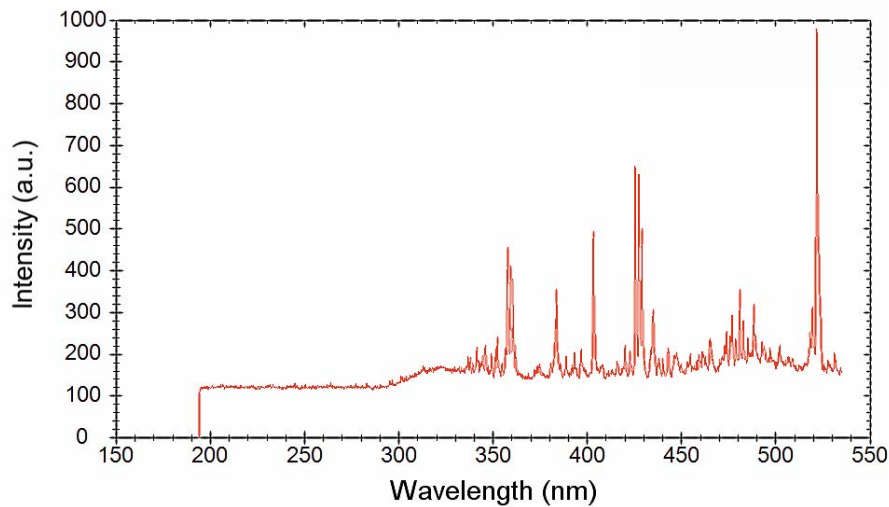


Fig. 7: Arc-welding plasma captured by means of POF sensor during the field tests.

4.- Conclusion

In this paper a new optical sensor based on the use of a POF cable for orbital arc-welding monitoring has been presented. There is a great difficulty in obtaining a constant optical signal during orbital arc-welding due to the configuration and disposition of the weld head during the welding process. Input optics based on a cosine corrector attached to a silica optical fiber has been checked, but the appearance of a “shadow region” prevents a correct spectroscopic analysis from being completed.

By removing the external jacket of the POF cable, and winding it within the external section of the weld head, the acquisition of plasma radiation has been experimentally demonstrated. Several TIG welding experiments have been carried out in the laboratory to characterize the amount of light captured depending on the length of the POF cable (number of turns within the weld head). In addition, field tests have demonstrated the feasibility of the proposed sensor to be used in a real industrial scenario.

Although we have demonstrated the ability of the POF cable to capture the plasma radiation during the arc-welding process, it remains to be seen whether this kind of fiber can be used for a long period of time, as it might suffer some deterioration caused by the high temperatures to be found within the

weld head. A possible solution to this problem could be the use of high-temperature resistant POF cables.

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