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Journal of Materials Processing Technology 179 (2006) 219–224

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Emission spectrometry evaluation in arc welding monitoring system

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Abstract

This work describes exploratory experimental procedures implemented for the development of a non-intrusive and real-time sensor for weld defect tracking which uses emission spectrometry for measuring the electromagnetic content of the plasma-weld pool interface in the GMA welding arc. The welding process monitoring is carried out by calculating the iron (Fe) and the manganese (Mn) electronic temperatures within the welding arc column, admitting that the observed region is at local thermodynamic equilibrium. The temperature was calculated by utilising the relative intensity method, which is based on the Boltzmann and the Saha Laws and on the definition of the emission line intensity. The calculated electronic temperatures of the two elements were correlated with the position of welding defects, which have been introduced for simulation purposes. These simulated defects resulted in abrupt changes in the average and standard deviation temperature values, thus providing an indication of the presence of a defect.

Keywords: Spectrometry; Welding; Plasma; Welding monitoring

1. Introduction

For many years, several different monitoring techniques have been studied, attempting to develop a general technique capable of dealing with the inherent complexity of the arc welding processes. Such studies aimed mainly at developing methods of quality of the welds on-line controlling, in order to prevent the needs for the costly and time consuming post weld inspection processes. The innovations generated by these studies are based on the physical phenomena involved in the arc welding processes, mainly those related to the plasma arc and its influence on the weld pool [1]. The applied techniques range from numerical simulation of the arc [2], image analysis [3], sound spectrum analysis and electromagnetic emission analysis [4–6] to the use of intelligent systems, based on neural networks and fuzzy logic [7].

This work describes a study on the possibility of utilising the electromagnetic emission of the arc welding plasma column for monitoring the presence of weld defects. The proposed method uses the electronic temperature, calculated from the intensities of the emission lines in the electromagnetic spectrum within the visible region, as an indicator of change in the expected quality. Some specially chosen emission lines can also give indication of contamination of the weld bead with hydrogen. This makes it possible for a control system to act before a deleterious effect can affect permanently the quality of a weld.

1.1. Emission spectrometry and plasma characterisation

The term "Spectrometry" stands for a set of experimental techniques used for measuring the electromagnetic spectrum that results from phenomena such as absorption, emission or diffraction of electromagnetic radiation by atoms or molecules. These techniques are generally analytical and, as such, may produce relevant data for the analysis of welding processes [8]. According to the Quantum Theory, atoms and molecules can only exist in a steady energy states, which are characterised by discrete amounts of energy that are specific to each atom or molecule.

When a change of energy state occurs in an atom or a molecule, their electrons absorbs or emits the specific amount of energy, which is strictly necessary for taking it from one energy state to another. Such change of energy state is generally accompanied by emission or absorption of light, which wave length, λ, is related to the energy of both states [9], according to the Eq. (1)

$$E_i - E_n = \frac{hc}{\lambda} \tag{1}$$

in which E_i is the energy in the lower state, E_n, the energy in the higher state, h, the Planck constant and c is the light speed.

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doi:10.1016/j.jmatprotec.2006.03.088

The emission spectrometry is generally used as a means of identifying the electromagnetic radiation wavelengths emitted by atoms or molecules of a substance due to a change on their energy state. Such wavelengths provide information on thermodynamic and quantum parameters that are necessary for calculating properties of interest. In the specific case of the welding process, a qualitative analysis (identification of chemical elements) allows the detection of weld contamination [10], helps in the selection and qualification of shielding gases [11] and provides a means of studying the rate of dilution in dissimilar metal welding [4]. On the other hand, the quantitative analysis involves the measurement of the intensities of each different wave length emitted by the plasma radiation and provides a means of calculating the most important plasma properties: its electronic temperature and its density.

1.2. Calculation of the plasma temperature

The plasma temperature is calculated from the temperature of the electrons (kinetic temperature) admitting the validity of the local thermodynamic equilibrium (LTE) hypothesis. This means that the particles have an energy distribution given by the Maxwell equation and that the collision processes are dominant relative to the radiation processes, i.e., the temperature of the electrons is similar to the temperature of the heavy particles [12].

The LTE hypothesis can be verified by means of applying the Eq. (2) [12], in which N_e is the electronic density [m^{-3}], T_e the electron absolute temperature [K] and ΔE is the difference of the transition energy intervals [eV].

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

Studying several works dealing with the LTE hypothesis, Vilarinho [13] concluded that its validity is restricted to the centre of the electric arc column. Such a conclusion defines the region to be observed by the optical equipment used for the emission spectrometry.

The typical value of the electronic density (Eq. (2)) in the GMAW process, calculated by Lacroix et al. [4], is $N_e \geq 1.81 \times 10^{19}\ m^{-3}$. This result is used in the present work. In the case of the LTE hypothesis being valid, the Maxwell, the Boltzmann and the Saha laws can be applied; the Maxwell and the Boltzmann laws being used for the plasma temperature calculation and the Saha law, for the calculation of its electronic density [14].

The temperature of the electrons within the plasma column is obtained by using the relative intensity of several emission lines [12]. According to Eq. (3), the emission line intensity for a transition from state "m" to state "n", I_{mn}, depends on the transition probability, A_{mn} (in units of s^{-1}), on the density of the higher level of energy, N_m (in units of m^{-3}), on the Planck's constant, h (in units of J s) and on the frequency, ν_{mn} (in s^{-1}).

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

The Boltzmann law can be stated as in Eq. (4)

$$N_m = \left(\frac{N}{Z(t)}\right) g_m \exp\left(\frac{-E_m}{kT}\right) \quad (4)$$

in which N is the total density of the energy level, g_m the statistic weight, $Z(t)$ the partition function, k the Boltzmann constant ($k = 8.6173 \times 10^{-5}$ eV K^{-1}), E_m the energy in the higher level and T is the absolute temperature. Applying Eqs. (4) into (3) and taking into account the relation between the wave length, the electromagnetic wave travel speed (the light speed, c) and the frequency, with some algebraic manipulation it is possible to obtain Eq. (5).

$$\ln\left(\frac{I_{mn}\lambda_{mn}}{A_{mn} g_m}\right) = \ln\left(\frac{Nhc}{Z}\right) - \frac{E_m}{kT} \quad (5)$$

Eq. (5) can be viewed as a first order polynomial in the independent variable "E_m", assuming that the absolute temperature, T, and the term "ln(Nhc/Z)" are constant. Consequently, the left side of Eq. (5) could be considered as a dependent variable of the polynomial. Therefore, if it is plotted as a function of the independent variable (the energy of the higher level E_m) for a set of emission lines, for which the values of A_{mn} and g_m are available (National Institute of Standards and Technology (NIST) http://physics.nist.gov/cgi-bin/AtData/lines_form), the angular coefficient of the resulting linear regression line would be a good estimate for the term"$-1/kT$", from which the corresponding absolute temperature could be calculated [4].

The temperature of the electrons may also be estimated by using the ratio of the relative intensities of two emission lines (indices 1 and 2 in Eq. (6)) of the same chemical element, as proposed by [15]. This method takes account of the changing density distribution along the welding plasma column and does not require the calculation of the time-consuming, spatially resolved lateral line intensity measurements in order to calculate the inverse Abel Transform [16]. Since this method involves recording the total spatially integrated radiation line intensities over the plasma diameter, it was obtained only the temperature at the centre of the plasma column [15], using a very simple and straightforward experimental setup.

$$T_e \approx \frac{E_{m(1)} - E_m}{k \ln[E_{m(1)} g_{m(2)} I_{(1)} A_{mn(2)} \lambda_1 / E_{m(2)} g_{m(1)} I_{(2)} A_{mn(1)} \lambda_2]} \quad (6)$$

in which $I_{(i)}$, $i = 1$ and 2, are the relative intensities of two emission lines, as acquired by the measurement system, and f_{mn} is the damping force of the transition m–n, which is tabulated. This method is better than the previous in a sense of implementing a real time monitoring system. The emission lines to be selected must satisfy the condition $E_{m(1)} - E_{m(2)} > kT$ in higher energy levels [5].

2. Experimental procedure

In order to experimentally evaluate the theory develop in the previous section, an experimental apparatus was implemented. A welding robot, which was responsible for moving the GMAW torch along a pre-defined welding path, together with a support for the optical equipment (collimating lens, with focal distance 11 mm, and one end of the 2 mm core diameter optical fiber) were used for producing the weld beads from which the data was to be acquired. The other