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Testing electromagnetic radiation of welding arc in TIG method from welding process monitoring point of view

Introduction

The observation of a welding arc and analysis of results can be used in assessment of welding process stability and correctness. Information related to a welding arc can be obtained by registering and analysing a sound emitted by an arc or by analysing a course of momentary values of electric quantities characterising an arc (intensity of arc welding current and arc voltage) [1]. Commonly applied methods of monitoring welding processes through a welding arc (the so-called "through the arc sensing) [2] are based primarily on measurements and registration of welding current intensity and welding arc voltage. The aforesaid methods also involve the registration of a shielding gas flow rate, welding rate and filler metal feeding rate. Monitoring is carried out by means of specialist recording equipment or universal measurement cards [1, 3]. Measurements of welding current intensity and welding arc voltage are used in assessing of welding process stability, particularly, if one applies advanced signal analysis [4].

A new approach to assess the stability of welding processes and the quality of welded joints is the analysis of welding arc radiation. The method was first used in the control of a welding arc length in the MAG method in 1966 [5] and was further developed in works [6, 7]. The issues related to radiation emitted by an electric arc are also investigated at Polish research centres. The result of this investigation is, among others, monographs [8-10]. The aforementioned publications, however, are not directly related to issues of monitoring arc welding processes.

New monitoring methods require the application of advanced measuring equipment, which, in most cases, must be adapted for welding-related measurement needs.

Welding arc radiation

The sources of radiation in an electric arc are, among others, arc column, near-electrode areas, liquid metal transported by an arc and a heated terminal of an electrode wire. A range of lengths of emitted light waves and their spectral composition depends on welding parameters, arc burning atmosphere, types of base and filler metals and a number of other parameters [11]. Figure 1 presents an image of a 2 mm-long welding arc in the TIG method at a welding current of 100 A. Figure 2 presents an image of a welding arc depending on current intensity and arc length. It can be observed that, in case of a constant arc length, an increase in welding current intensity results in a more stable and more symmetric welding arc of the TIG method.

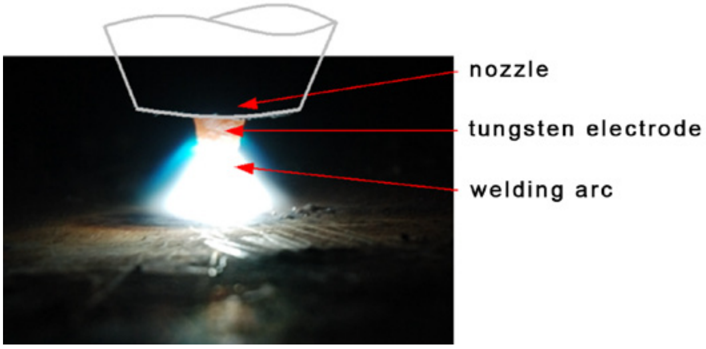

Fig. 1. Shape of welding arc in TIG method, welding current intensity I=100A, welding arc length L=2 mm

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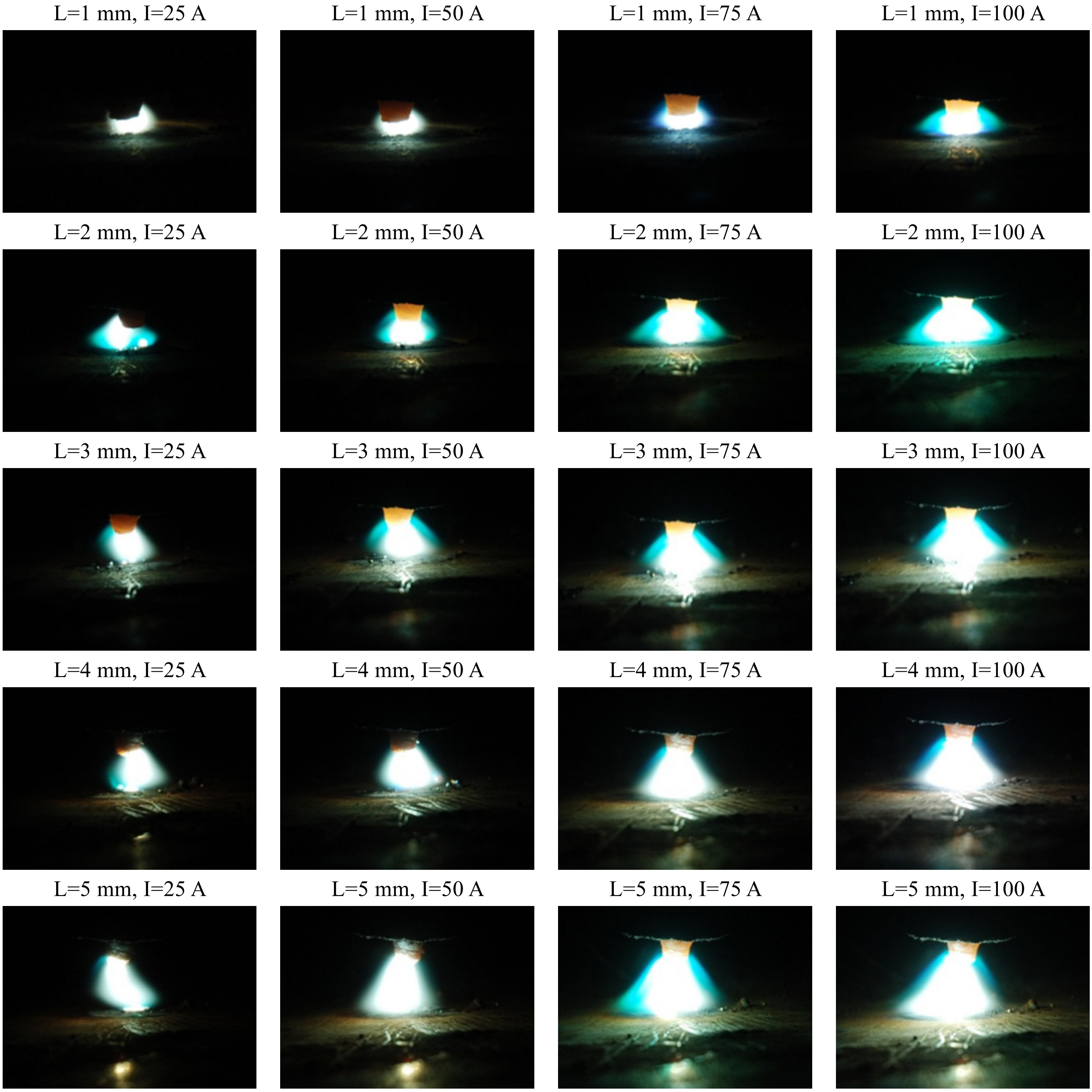

Fig. 2. Image of welding arc in TIG method for arc length in range from 1 to 5-mm and current intensity from 25 to 100 A; shielding gas: argon

Energy emitted in an arc column is mainly scattered by conduction and convection. Emission of electromagnetic radiation constitutes 10÷15% of energy supplied to an arc [11]. Heat radiation, the source of which is a body emitting high temperature, is characterised by a continuous radiation spectrum. The source of a continuous spectrum in the area of a welding arc is mainly a liquid weld pool [12]. The characteristic radiation of atoms and ions in an arc is discrete. This type of radiation is analysed in reference publications as plasma radiation.

Plasma of a temperature contained in a range between several eV and a few dozen keV (in energy scale 1 eV = 11600 K) emits infrared radiation, visible radiation, ultraviolet radiation and X-ray radiation, which, due to the mechanism of emission can be divided into three basic types [14]:

1. linear radiation emitted during the transition of atoms or ions from one discrete energy level to another (transition between bound states);
2. recombination radiation accompanying a capture of a free electron by one of the discrete atom or ion levels (transition between a free state and bound states);
3. radiation of free electron retardation in an ion field (transitions between free states).

The total radiation of welding arc plasma is the sum of the continuous radiation and linear radiation of spectral lines [10, 15]. This sum can be written as [15]:

$$\varepsilon_\lambda = \varepsilon_{\lambda,c} + \sum \varepsilon_{\lambda,L} \tag{1}$$

where: $\varepsilon_{\lambda,c}$ - intensity of continuous spectrum radiation, $\varepsilon_{\lambda,L}$ - intensity of spectral line; the summation on the right side of the equation is carried out including all lines lying in a given area.

For optically thin plasma, the intensity of continuous spectrum radiation can be written in the following form [15] :

$$\varepsilon_{\lambda,c} = k_{\lambda,c}(T) \cdot B_\lambda(T) \cdot \left(1 - \exp\left(-\frac{hc}{\lambda kT}\right)\right) \tag{2}$$

where: $B_\lambda(T)$ is the Planck function for a black body, and $k_{\lambda,c}(T)$ is a total absorption coefficient, T – arc temperature [K], h - the Planck constant (6.6262×10^{-34} [Js]), c - speed of light in vacuum (2.9979×10^{8} [ms^{-1}]), λ - wavelength [nm], k - the Boltzmann constant 1.38×10^{-23} [JK^{-1}].

The formula for continuous radiation intensity applies irrespective of whether plasma is in a state of thermal equilibrium or not.

The intensity of a spectral line $\varepsilon_{\lambda,L}$ is expressed by the following formula [15] :

$$\varepsilon_{\lambda,L} = \frac{hcg_q A_{qp} N_e N_i}{8\pi\lambda U_i(T)} \left(\frac{h^3}{2\pi mkT}\right) \cdot \exp\left(\frac{E_{i,q} - \Delta E_i}{kT}\right) \cdot P_{qp}(\lambda) \tag{3}$$

where: g_q – statistical weight factor of the upper level; A_{qp} – transition probability; $E_{i,q}$ – upper level ionisation energy; ΔE_i – ionisation potential reduction; P_{qp} – line profile, N_e - density of electrons, N_i - density of ions, U_i - statistical weight factor of ion, m - particle mass.

The spectral distribution and intensity of thermal radiation depend on the temperature of a radiating body. Black bodies of a temperature of up to 500 K emit mainly infrared radiation of wavelength of > 2 µm. Bodies of a temperature exceeding 1000 K emit, in addition to long-wave infrared radiation, also near infrared radiation in the wavelength range of 0.78 µm ÷1.4 µm and very little, below 1%, visible radiation. Bodies of a temperature exceeding 3000 K emit, in addition to infrared radiation and visible radiation, also some (0.1%) long -wave ultraviolet radiation. Only bodies of a temperature exceeding 4000 K emit ultraviolet radiation shorter than 315 nm [11].

Welding arc radiation intensity is the highest in the wavelength range between 200 nm and 1300 nm [16]. The fraction of infrared, visible and ultraviolet radiation in the spectrum of welding arc radiation depends on a welding technology and, in each technology, on welding parameters [11, 16].

The greatest intensity of visible radiation among arc welding processes can be observed in MIG/MAG, MMA, TIG and plasma welding. It was ascertained that the intensity of ultraviolet radiation increases with a square of welding current intensity and that visible radiation intensity does not rise so intensively [11, 16].

The intensity of ultraviolet and visible radiation emitted during metal arc welding and welding with cored electrodes (MIG/MAG methods or self-shielded arc welding) in the presence of welding fumes is lower than in the case of TIG welding (for similar welding current intensity). In the same welding conditions the intensity of infrared radiation does not change significantly. During submerged arc welding visible radiation and ultraviolet radiation is absorbed by a flux layer [11].

The characteristic radiation of ions and atoms in an arc is discrete; argon, iron, oxygen and nitrogen atoms and ions being the main source of radiation. The radiation intensity of other elements is significantly lower. The wavelength range of visible radiation contains mainly spectra of iron, oxygen, nitrogen and, only partially, argon (whose ionisation potential is significantly higher) [17]. The latter also means that the emission of light by argon atoms and ions occurs at higher arc temperatures than temperatures obtained during welding in e.g. Ar+CO_2 mixes.

Examinations of a discrete spectrum provide information about a temperature emitting particle radiation; this being due to the fact that the excitation of a particle requires a supply of specific energy, a measure of which can be temperature. The source of this type of radiation in a welding arc is mainly arc column plasma as well as metal transported by an arc, slag and the surface of elements being welded [18]. The energy of areas in the vicinity of the anode and cathode of a welding arc is used mainly for heating and melting of an electrode and base metal. It is known that the potential and kinetic energy of electrons is transformed into thermal energy on the surface of an anode and causes its intensive heating [17].

The radiation of a welding arc is a complex phenomenon depending on many welding parameters. In order to be able to apply the radiation of an arc in the accurate and reliable monitoring of a welding process, one should create a model binding the intensity of welding arc visible radiation with welding parameters [19].

A welding arc can be treated as a point source of radiation. Such an approach, however, appears inadequate in many applications. It seems more proper to treat an arc as a cylindrical source of radiation (Fig. 3) as such a model better reproduces the actual shape of a welding arc and facilitates accurate examination of arc radiation. For this reason, the aforesaid model will be discussed in more detail. A cylindrical model can also be simplified and a welding arc can be presented as a hemisphere. Such an approach is used in designing of systems for monitoring of automated welding processes, based on visual systems [20, 21].

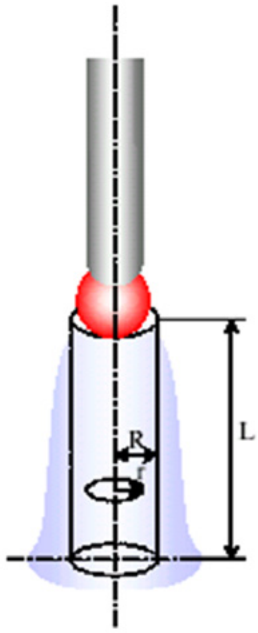

Fig. 3. Model of welding arc in TIG method [6]

A welding arc column is composed of three types of particles: electrons, ions and neutral atoms. It is assumed that an arc column is in a state of local thermodynamic equilibrium, at which electron collisions play an important role in excitation and ionisation.

Equation 2 illustrates the emission of welding arc radiation of a continuous spectrum. After taking into consideration the dependence between a wavelength and frequency c/λ=ν and the Planck function for a black body, the Rayleigh-Jeans law is satisfied when hν/kT<<1. In such a situation, equation 2 can be simplified as:

$$\varepsilon_\nu = k'(\nu)\ \frac{2\nu^2}{c^2} kT_e \qquad (4)$$

where: ν - frequency [Hz], T_e - kinetic temperature of electrons [K]. The fit of equation 2 with equation 4 is better than 5% for $\lambda_L T>4.3$ cmK, where λ_L is a wavelength expressed in cm. The right side of equation 4 amounts to 1 (approximately) for infrared and visible radiation. In addition, under atmospheric pressure and in a normal range of welding current, the temperature of an electron is close to the temperature of an arc. Taking into consideration the foregoing and omitting differences of temperature one can write as follows:

$$\varepsilon_{v} = k'(v)\ \frac{2v^2}{c^2}kT \qquad (5)$$

where: T is the temperature of an arc [K].

In order to simplify the discussion, the gradient of temperature changes along the arc axis has been passed over. By combining the emissivity factors for various arc areas, the energy radiated from the whole arc can be expressed as:

$$B_{iv} = \iiint \varepsilon_{v} dv \qquad (6)$$

After calculating emissivity factors in the whole welding arc and assuming that electric conductivity and voltage gradient are constant as well as after taking into consideration the impact of the visible radiation of a liquid metal pool one can write as follows:

$$B_{iv} = G_1 L I^{\gamma}\left(e^{\frac{G_2}{I}} - \frac{1}{2}\right) + G_3 I^2 + G_4 \qquad (7)$$

where:

γ, G_i – constants, L – arc length, I – current intensity.

Equation 7 provides the image of a relation between the visible radiation of a welding arc and welding parameters, including the relation between current intensity and arc length. The authors of model [6] indicate that the equation is satisfied for a welding arc when current intensity is up to 150 A. In case of higher intensity, the density of current is not constant in the whole volume of a welding arc.

Investigation of welding arc radiation

The research conducted so far has been mainly focused on the examination of arc luminance [22], the impact of arc radiation on the welder's health [23], health-protecting systems and the development of systems for tracking the axis of a joint (welding torch position) [2]. The analysis of a visible radiation spectrum emitted by a welding arc is used to test the distribution of temperature in an arc [25], calculate the average temperature of a welding arc [26], determine the amount of hydrogen in a gas shield [27] and determine the temperature of a liquid metal pool [28]. The analysis of a welding arc radiation spectrum is helpful in the development of a technique of photographing a welding arc [29]. Spectroscopic methods are a useful tool for investigating spins of a shielding gas after leaving the gas nozzle in TIG and MIG/MAG methods [30], a relation between the spectral distribution of an arc and the type of a material being welded [31] and the distribution of electron density [32].

The investigation of welding arc visible radiation in MIG/MAG methods was also used in the monitoring of a manner in which a metal is transferred in an arc [33, 34]. Methods utilising electric signals (measurements of welding arc voltage and welding current intensity) are effective only for observing a short-cut arc welding process and with a coarse drop metal transfer in an arc. When metal is spray-transferred, the signal/noise ratio is too low and, in such a situation, greater accuracy is obtained by measuring the intensity of welding arc visible radiation [33, 34]. The method based on the measurement of welding arc radiation is also used in tracing the length of an arc in TIG [35, 36] and MIG/MAG [34] methods.

Other, equally important research is focused on plasma. Methods applied in the plasma-related investigation are those of emission spectroscopy and laser radiation scattering (laser spectroscopy). The aforesaid methods make it possible to calculate such plasma parameters as the temperature and concentration of atoms (ions, electrons) [37].

Emission spectroscopy is a passive method, in which electromagnetic radiation originating from plasma (one or many spectral lines) is registered and analysed. The main advantage of this method is the simplicity of carrying out measurements. The method requires an optical focusing system, monochromator or spectrometer and detector (e.g. a photomultiplier or CCD matrix). The major disadvantage is the fact that radiation being registered is total radiation emitted from plasma. In order to obtain measurement data from one specific measurement point it is necessary carry out the Abel transformation [38]. Another disadvantage is the necessity to assume that plasma is in a state of local thermodynamic equilibrium and is optically thin.

Laser spectroscopy is a more universal method, yet it requires the source of laser radiation and a detection system. The method of laser spectroscopy enables the determination of plasma parameters in a given point. In some cases, laser spectroscopy makes it possible to calculate plasma parameters without assuming that plasma is in thermodynamic equilibrium. The technique utilises the Rayleigh scattering, Tomson scattering, laser-induced fluorescence and diphoton laser-induced fluorescence [37].

Plasma radiation registered in measurements perpendicularly to the discharge axis is a sum of contributions from various layers (Fig. 4). The so-called Abel transform [37, 38] makes it possible to determine ε(x) on the basis of known I(x).

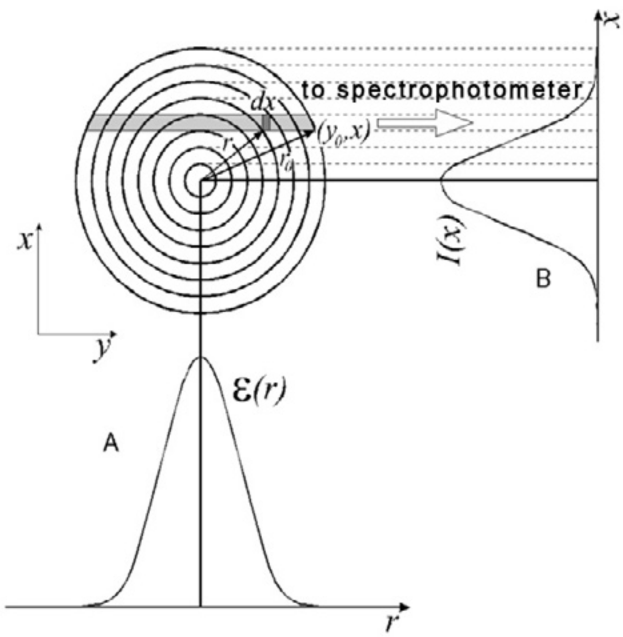

Fig. 4. Sectional view of plasma column, discharge axis is perpendicular to paper sheet plane: A- radial distribution of emission factor, B – side view of intensity distribution. I(x) – distribution of radiation intensity in plane perpendicular to direction, in which plasma is observed, x – distance from direction of plasma observation [38]

When plasma is characterised by cylindrical symmetry in the sectional view under observation and the phenomenon of self-absorption is not present, the distribution of radiation intensity in the plane perpendicular to the direction of plasma observation is expressed by the following formula [38]:

$$I(x) = 2 \cdot \int_{x}^{r_0} \frac{\varepsilon(r) \cdot r}{\sqrt{r^2 - x^2}} dr \qquad (8)$$

where: ε(r) – intensity of radiation emitted by plasma on the unit of thickness of a layer distant from the discharge axis by *r*, x – distance from the direction of plasma observation (Fig. 4), $2r_0$ – diameter of an area where plasma is present.

The so-far research into welding arc plasma aimed, among others, at the creation of a mathematical-physical model of an arc [39, 40] which could be useful in designing new welding devices [41]. Also important, from the practical point of view, is research aiming to determine the impact of electrical parameters of an arc on its properties [42] as well as the changes of the chemical composition of a shielding gas [43] and a magnetic field on the arc blow [44]. Fundamentally important, however, is the possibility of calculating the thermal efficiency of an arc [45]. Many conducted experiments aimed to calculate the distribution of arc temperature [46], the speed of electrons and ions in an arc, electronic work function [47] and the state of thermodynamic equilibrium [48]. Modern welding methods such as A-TIG welding encouraged the authors [49] to test the impact of additional elements and compounds intentionally supplied to the area of a welding arc on its properties.

On the basis of the analysis of reference publications concerning welding arc research one can draw a conclusion that considerable attention is given to the phenomenon of welding arc radiation and the impact of arc burning stability on emitted radiation, yet there are no implementations of results obtained in related research.

An important issue of arc-related research is the determination of the impact of individual factors on the width of spectral peaks. A typical shape of a spectral peak is presented in Figure 5 along with characteristic quantities: x_c – wavelength of central line, FWHM (Full Width at Half Maximum) – width of spectral line, I_{max} – maximum value of radiation intensity for a given spectral line. The natural length of a spectral line [28, 50] is the result of the finite lifetime of energy levels. The width is the greater, the shorter the lifetime of an energy level is. The profile of an emission line, resulting from natural extension, is the Lorentz distribution.

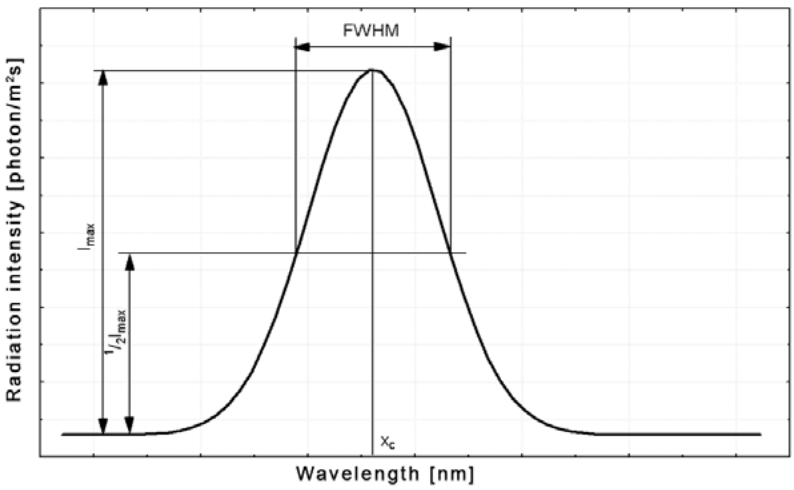

Fig. 5. Typical shape of spectral line [51]

Another important factor is the Doppler extension of spectral lines, connected with the motion of radiation-emitting particles. If an emitter has a speed component of a direction compatible with the direction of observation, a relative change of wavelength related to a change of frequency is produced by the Doppler effect. In case of thermal movements, when the distribution of speed of emitting particles is the Maxwell distribution, the profile of an emitted spectral line is the Gaussian profile [8].

Another type of extension which can be encountered while analysing spectral lines is the pressure extension of spectral lines. This type of spectral line extension is the result of collisions of emitter particles with other particles. They can limit the lifetime of excited atomic levels and thus cause the extension of a line profile, in this case – the Lorentz profile. As a rule, one differentiates three types of pressure extension i.e. the resonant, van der Waals and Stark extension [8].

The arrangement of measurement system components is a factor causing additional extension of a spectral line. In this case, the equipment profile is Gaussian. Theoretically, the equipment function of a spectrometer should be linearly dependent on the wavelength. In fact, the equipment profile is the combination of a function connected with the matrix of a detector and functions related to optical elements of a spectrometer system [8]. Factors causing the extension of spectral lines can be divided into those producing the Lorentz and Gaussian shapes of line profiles. Their impact on the value of extension varies and may depend on conditions present in plasma. A spectral line resultant profile is a function being the combination of the Lorentz and Gaussian [50] functions called the Voigt profile [8, 52].

It should be noted that a photoelectric detector is reached both by useful signals and background radiation. As a result, at the CCD detector output there are useful signals accompanied by noise originating from the background. In order to eliminate the impact of background radiation, one should deduct it while analysing the distribution of welding arc radiation intensity.

Due to the resolution of converters one should take into consideration the fact that registered files are a "cluster" of several spectral lines of a given element (Fig. 6) or even of a few elements of various levels of ionisation. Therefore, the matching of a shape function matters only for the determination of the gravity centre for such a group of files. The first element of a system for monitoring welding processes is the development of a method for identification and measurement of quantities characterising registered spectral peaks such as the peak width, the location of maximum and amplitude. The investigation into which function better describes the profile of a peak ("cluster" of spectral lines) seems to be decisive for the detection of welding process disturbance. Peak profiles can be the Gaussian, Lorentz and Voigt functions (Fig. 6).

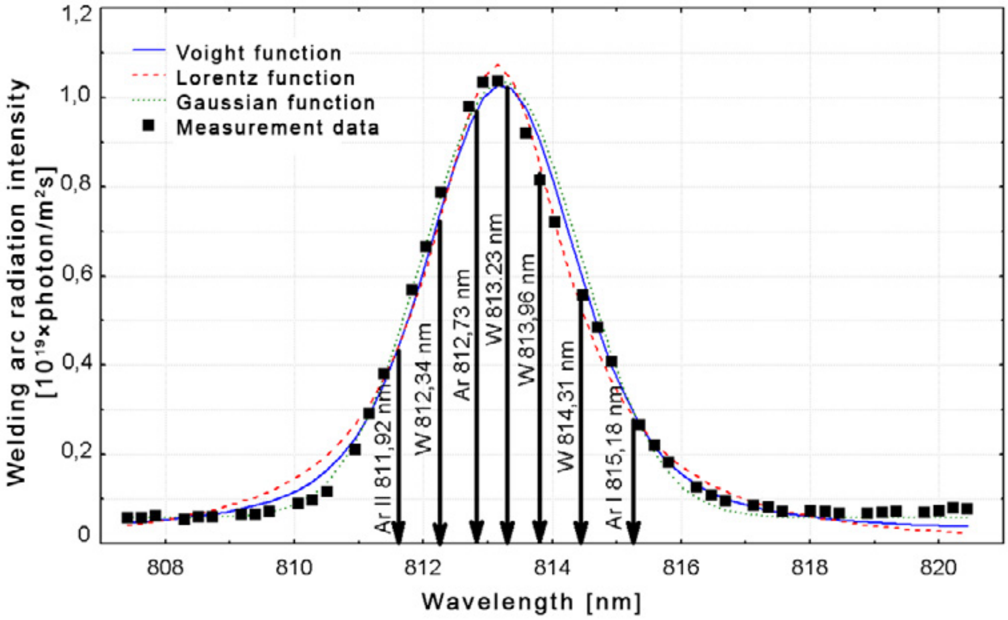

Fig. 6. Exemplary peak matched with Gaussian, Lorentz and Voigt functions, I=200 A, L=3 mm, 100 % Ar with marked selected spectral lines

The matching with functions is usually carried out using the least squares method (e.g. the Levenberg-Marquardt algorithm). One can also adapt specialist software for this activity. On the basis of matched parameters of a function one can calculate the location of the spectral line maximum (x_c) and the width of a spectral line (FWHM). During the development of experimental data, one should also take into account the so-called additive constant y_{00}, the presence of which results from additional signals registered by measuring equipment.

Next, on the basis of equation (7) one can determine the dependence binding the intensity of welding arc radiation (energy radiated for a given spectral line x_c) B_{iv}, arc length and welding current intensity. Using a computer programme, one can use collected data to calculate the coefficients G_i and γ.

Values of parameters characterising a welding process can be determined by minimising the sum of squares

$$\chi^2 = \sum_l \sum_k \frac{1}{(\Delta B_{kl})^2} \left[B_{kl}(I_k, L_l, \lambda) - \widetilde{B}_{kl}(I_k, L_l, \lambda, \{g_i\}) \right]^2 \qquad (9)$$

where: I_k - welding current intensity; L_l - welding arc length; $B_{kl}(I_k, L_l, \lambda)$ - intensity of light of wavelength λ registered during welding with current of intensity Ik, when welding arc length amounted to L_l; ΔB_{kl} - uncertainty of determined light intensity $B_{kl}(I_k, L_l, \lambda)$; $\widetilde{B}_{kl}(I_k, L_l, \lambda, \{g_i\})$ - theoretical intensity of light of wavelength λ, expressed by formula (7), registered during welding with current of intensity I_k, when welding arc length amounted to L_l; $\{g_i\}=\{G_1, \gamma, G_2, G_3, G_4\}$ - set of parameter values present in formula (7).

The uncertainty of the determination of i-th parameter gi ϵ $\{gi\}=\{G_1, \gamma, G_2, G_3, G_4\}$ is determined by means of a method described in publication [53]:

$$\varepsilon_i = \frac{\chi^2}{m_p - m} h_{ii}^{-1} \qquad (10)$$

where: h_{ii}^{-1} - component *ii* of the inverse Hessian matrix; χ^2 - sum of squares of deviations of theoretical values from experimentally obtained results; m_p- number of experimentally obtained results; m - number of parameters determined through matching. The components of the Hessian matrix are defined by formula [53]:

$$h_{ij} = \frac{\partial^2 \chi^2}{\partial g_i \partial g_j} = -2 \sum_l \sum_k \frac{1}{(\Delta B_{kl})^2} \left[B_{kl}(I_k, L_l, \lambda) \frac{\partial^2 B_{kl,teor}(I_k, L_l, \lambda, \{g_i\})}{\partial g_i \partial g_j} - \frac{\partial B_{kl,teor}(I_k, L_l, \lambda, \{g_i\})}{\partial g_i} \frac{\partial B_{kl,teor}(I_k, L_l, \lambda, \{g_i\})}{\partial g_j} \right] \qquad (11)$$

Own research

The research-related tests were carried out on a station for mechanised TIG welding. A measurement system applied in the tests (Fig. 7) enabled measurements of welding current intensity, welding arc voltage, filler metal feeding rate and welding arc radiation intensity. The intensity of welding current was measured with a current probe LEM PR1001 based on the Hall effect. The voltage of a welding arc was measured with a voltage transducer LEM LV 25-P . A filler metal feeding rate was measured with a rotary measuring impulse transmitter. The transmitter was connected directly to a system of filler metal feeding rollers. The spectral distribution of a welding arc was recorded with a spectrophotometric card PC 2000 ISA-A Ocean Optics, provided with a Sony-made CCD detector type ILX511. The card made it possible to examine the spectrum of welding arc electromagnetic radiation in a range from 200 nm to 1100 nm. A measurement time of 3 ms enabled on-line registration of spectral distribution. A measurement range used in the tests was between 350 nm and 850 nm.

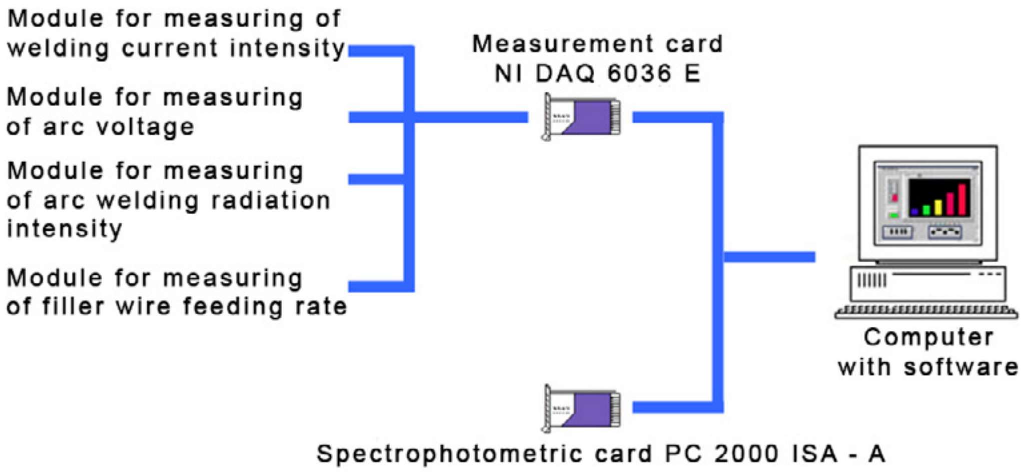

Fig. 7. Layout of measurement system for monitoring of welding process

The intensity of arc radiation was also registered with a photodiode of a spectral range from 400 nm to 1100 nm. The measurement system applied in the registration (Fig. 7) contained also an amplifying system, interference filter, focusing system and an optical fibre.

Electric signals corresponding to the intensity of arc visible radiation and signals from a welding circuit were registered by a recording device utilising a measurement card NI DAQ 6036E in a computer. Next, signals recorded by the device underwent an analysis.

The testing station was also provided with a slide for moving a test plate and a cylindrical copper element cooled with water. A TIG welding torch was fitted to a system of slides enabling the adjustment of its position in both vertical and horizontal planes. Such a solution enabled precise setting of a distance between the welding torch and the surface of material (arc length). During tests the table with the test plate was moved, whilst the welding torch remained immovable. A DC welding device consisted of a universal welding source KEMPPI Pro 5000 with an attachment TIG Pro 400 or ESAB-manufactured device AristoTig, ESAB-manufactured cooler COOL 10 and a Binzel-made welding torch AUT WIG 400W. The tests also involved the use of LabView-based software for controlling the operation of a measurement card NI DAQ 6036E as well as Ocean Optics-developed software OII Base 32 for controlling the operation of a spectrophotometer. The measuring station made it possible to test the impact of parameters and disturbance of TIG welding with filler metal feeding on the spectral distribution and the intensity of welding arc radiation.

The tests carried out within this part of research made it possible to determine the impact of welding current intensity and welding arc length on the intensity of welding arc radiation. The tests included the measurement of radiation intensity at a welding current of between 40 A÷200 A and an arc length of 1, 2 and 3 mm as well as at a welding current of between 30 A÷300 A and an arc length of between 2 mm and 5 mm (Fig. 8). The tests were carried out for arc burning on a copper plate cooled with water.

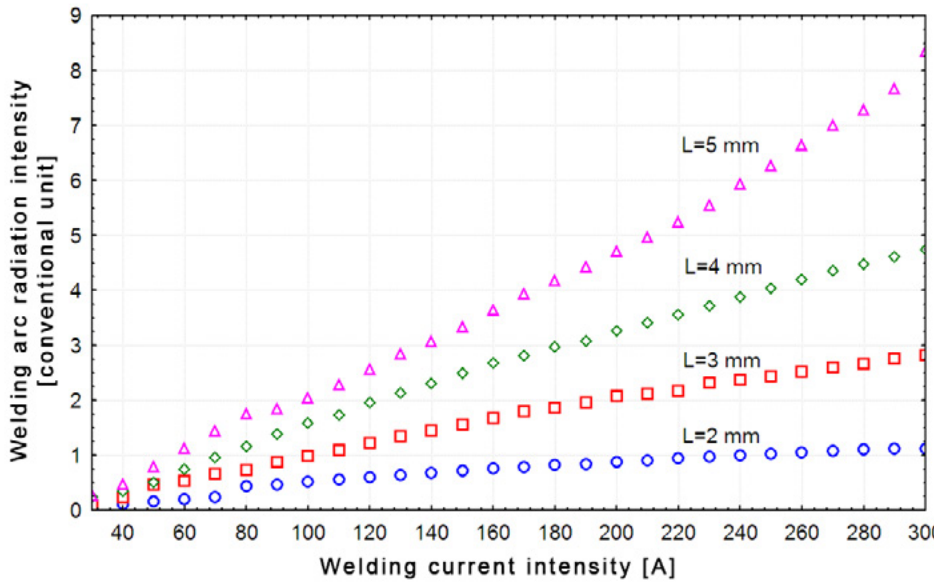

Fig. 8. Impact of change of welding current intensity in TIG method on intensity of welding arc visible radiation, at constant length of welding arc, for wavelength of 698 nm; shielding gas: argon

In order to determine the impact of welding parameters on the intensity of welding arc radiation, it was necessary to separate four exemplary spectral peaks (494.93, 606.31, 698.23 and 75285 nm) from registered spectral distributions. Figure 9 presents the impact of welding current intensity (at a constant welding arc length in TIG method) on the radiation intensity of selected spectral peaks. The analysis of registered signals revealed that a change of welding current intensity strongly affects a change of welding arc radiation intensity for a given wavelength. The aforesaid changes are more noticeable when a wavelength value increases. The foregoing is particularly visible if one compares the intensity of welding arc radiation for a peak of 494 nm and for a peak of 752 nm (Fig. 9).

The coefficients G_i (Tables 1 and 2) were calculated in equation (7) on the basis of collected measurement data i.e. arc length, arc radiation intensity and welding current intensity. While calculating constants, the following two cases were taken into account:

- theoretical model acc. to Zhang [6]; in this model, the coefficient γ=2, in such case one can write that:

$$B_{iv} = G_1 L I^2 \left(e^{\frac{G_2}{I}} - \frac{1}{2} \right) + G_3 I^2 + G_4 \quad (12)$$

- generalised model - coefficient γ is a parameter depending on measurement data.

Calculations were carried out with the use of equation (9) and taking into account two cases:

- ΔB_{kl} - uncertainty of determined visible radiation intensity is constant for all data and is not taken into account in calculations; in the case under discussion, worse matching will be for lower values,
- ΔB_{kl} - uncertainty of determined visible radiation intensity is not constant for all data and is taken into account in calculations.

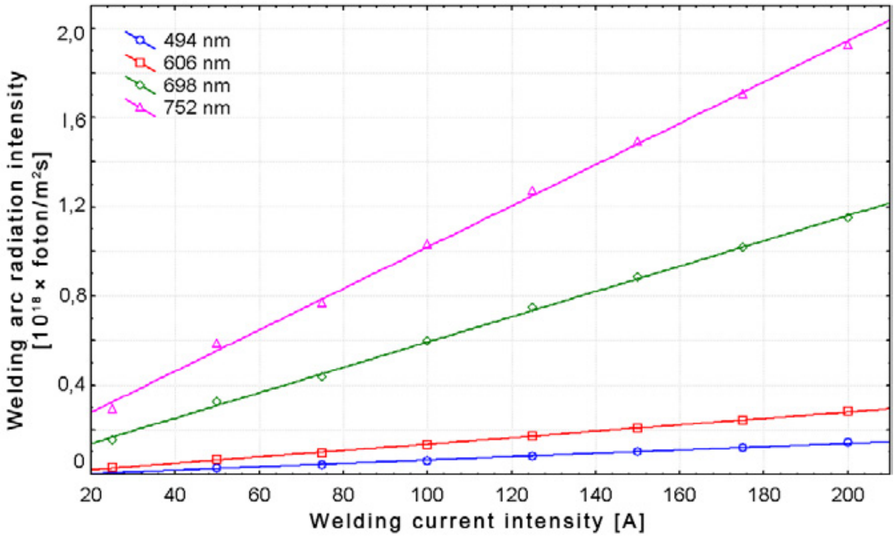

Fig. 9. Impact of change of welding current intensity in TIG method on intensity of welding arc visible radiation, at constant length of welding arc, for selected wavelengths; shielding gas: argon

Table 1. Calculated coefficients G_i for theoretical and generalised models for welding arc length of between 2 mm and 5 mm, ΔB_{kl} is constant

No.	Coefficient	Theoretical model	Generalised model
1	G1	$3.8(2)\times10^{-5}$	$1.11(1)\times10^{-3}$
2	G2	56(3)	9(2)
3	G3	$-4.4(1)\times10^{-5}$	$-3.98(12)\times10^{-5}$
4	G4	$1(57)\times10^{-3}$	$-1.8(6)\times10^{-1}$
5	γ	2	1.455(4)
6	χ^2 sum of least squares of deviations	7.33	3.6
7	correlation coefficient R_2	0.98	0.99

Table 2. Calculated coefficients G_i for theoretical and generalised models for welding arc length of between 2 mm and 5 mm, ΔB_{kl} is taken into account

No.	Coefficient	Theoretical model	Generalised model
1	G1	$4.6(2)\times10^{-5}$	$1.7(1)\times10^{-3}$
2	G2	34(2)	$2(65)\times10^{-2}$
3	G3	$-4.06(10)\times10^{-5}$	$-35.1(6)\times10^{-6}$
4	G4	$-1.09(16)\times10^{-1}$	$-11.4(9)\times10^{-2}$
5	γ	2	1.364(2)
6	χ^2 sum of least squares of deviations	5.75	1.07
7	correlation coefficient R_2	0.99	0.99

On the basis of calculations (Tables 1 and 2) indicating that the sum of the least squares of deviations is the lowest for the generalised model and with taking into account the weight ΔB_{kl}, equation (7) takes the final form as follows:

$$B_{iv} = 0{,}0017 L I^{1{,}364}\left(e^{\frac{0{,}02}{I}} - \frac{1}{2}\right) - 0{,}000035 I^2 - 0{,}114 \qquad (8.4.1.2)$$

The equation is satisfied when a wavelength amounts to 698 nm and a welding arc length is contained in a range 2 mm÷5 mm. A graphic illustration of the theoretical [6] and generalised models is presented in Figures 10 and 11. The tests were carried out for arc burning on a copper plate cooled with water.

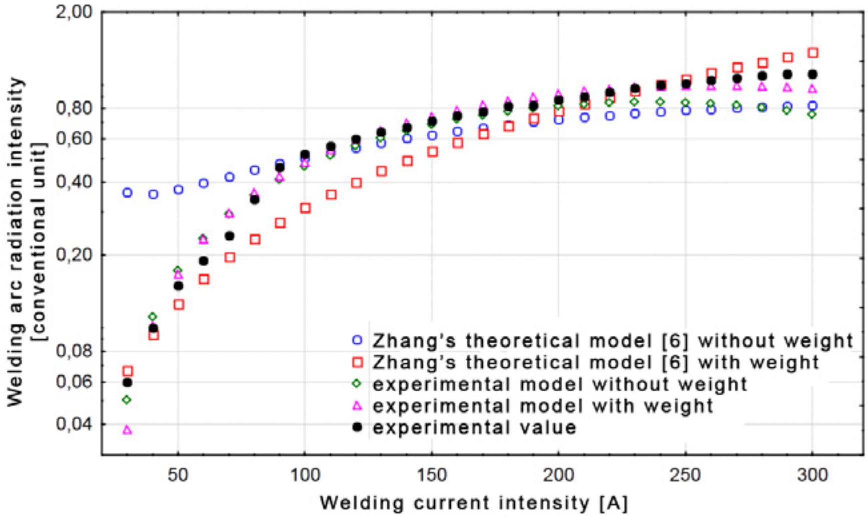

Fig. 10. Dependence of welding arc radiation intensity in TIG method on welding current intensity, for wavelength of 698 nm and arc length of 2 mm

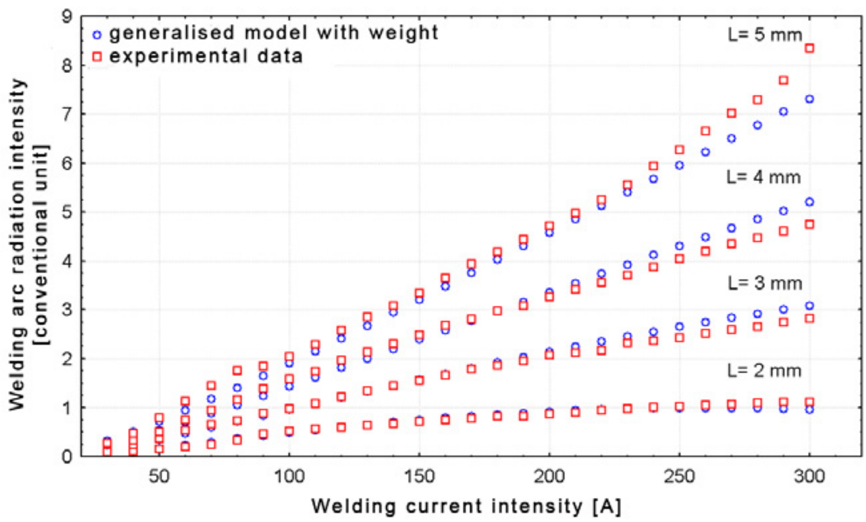

Fig. 11. Dependence of welding arc radiation intensity in TIG method on arc length L and welding current intensity, for wavelength of 698 nm and arc length of 2÷5 mm

Summary

The study presents the results of tests of welding arc radiation in TIG method. On the basis of the tests it was possible to come to the following conclusions:

- in case of a constant welding arc length, an increase in welding current intensity leads to an increase in arc visible radiation intensity,
- in TIG method an increase in an arc length causes an increase in welding arc visible radiation intensity,
- determination of parameter values (G_1, G_2, G_3, G_4 and γ) in the generalised semi-empirical model enabled better matching of a welding arc model for a 2÷5-mm range of welding arc lengths .

On the basis of the test results it is possible to state that welding arc radiation is a source of rich information about a welding process course and makes a valuable tool in the monitoring of a TIG welding process. The tests indicate the possibility of using technologically advanced spectrophotometers in the monitoring of welding processes. If applied in combination with optical fibre lines, the spectrometers could enable the real-time control of arc-based welding processes (TIG, MIG/MAG, PAW) as well as, due to the presence of a plasma cloud during welding with a laser beam, also the monitoring of the latter process. It should be noted that a spectrophotometric card enables the monitoring of intensity changes of many spectral peaks at the same time and thus makes it possible to obtain more information about an object being tested.

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