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MEASUREMENT OF ARC LIGHT SPECTRUM IN THE MAG WELDING METHOD

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Abstract

Welding arc light can be seen as a signal carrying essential information about the welding process and exploited in the monitoring of the welding process. Results of experimental research on the radiation of the welding arc in the Metal Active Gas (MAG) welding method are presented for an industrial platform. The methodology of calculation of the spectrophotometer spectral response is presented. The range of the tested wavelengths has been limited to visible radiation of the welding arc in the range of 340-500 nm. The conditions of arc burning were modified by changing the welding parameters. During experiments the welding current was changed in the range of 104-235 A. The analysis of the spectrum of the radiation of the welding arc is investigated. This method can be useful for the monitoring of arc welding and laser welding processes.

Keywords: MAG welding, monitoring, arc light emission, spectrophotometer card.

1. Introduction

Welding is one of the most economical and efficient ways to join metals permanently. It is a common way of joining two or more pieces of metal to make them act as a single piece or monolithic structure. Welding is used to join all of the commercial metals and to join metals of different types and strengths. This technology is vital to the economy. It is often said that up to 50% of the gross national product of the country is related to welding in one way or another [1]. The technology of welding is complex. Welding is continuing to grow, yet the industry is changing rapidly. Among these, Metal Active Gas (MAG) has become the most popular methods of arc welding. Sometimes [2] the MAG technique is called GMA (Gas Metal Arc), MIG/MAG (Metal Inert Gas/Metal Active Gas).

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The MAG welding process employs a continuous consumable solid wire electrode and an externally supplied active shielding gas. A scheme of the process is shown in Fig. 1. The electric arc is burning between the consumable wire electrode, which provides also the filler to the welded joint, and the workpiece, which is a part of the electric circuit. The wire is fed to the arc by an automatic wire feeder, of which both push and pull types are employed, depending on the wire composition, diameter, and welding application. The externally supplied shielding gas plays a dual role in the MAG welding method. Firstly, it protects the arc and the molten or hot weld metal from air. Secondly, it provides the desired arc characteristics through its effect on ionization. A variety of gases can be used, depending on the reactivity of the metal being welded, the design of the joint, and the specific arc characteristics that are desired. Constant voltage (DC) welding power supplies can be used. Either DCSP (Direct Current Straight Polarity) or DCRP (Direct Current Reverse Polarity) may be used, depending on the particular wire and desired mode of molten metal transfer, but the DCRP mode is far more common. The reason is that in the RP mode, electrons from the negative workpiece strike the positive wire to lose their kinetic energy in the form of heat to melt and consume the wire.

A distinct advantage of MAG welding is that the transfer of molten metal from the consumable wire electrode can be intentionally changed and controlled combining such parameters as: composition of the shielding gas, power source type, electrode type and form, arc current and voltage and wire feed rate. There are three predominant metal transfer modes: spray, globular, and short circuiting. There is also a pulsed current or pulsed arc mode [3].

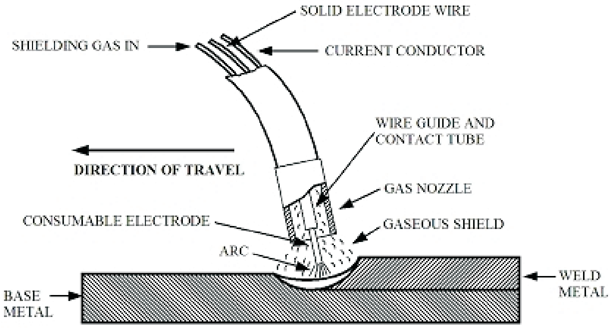

Fig. 1. Illustration of MAG welding process.

Sources of visible radiation in the welding arc are the following: the arc column, the regions close to the electrodes, liquid metal transported across the welding arc, the molten pool, the heated region of base material around the molten pool, and the heated end of the electrode wire. Hot slag may also be a source of radiation. The length range of the emitted light waves and their spectral composition depend on the welding parameters, the atmosphere in which the arc glows, the kind of the base and consumable material, as well as on several other parameters [4-7]. The intensity of radiation produced by the welding arc is a function of the welding process itself and of the welding variables. For example, less ultraviolet and visible energy is radiated at comparable current levels during shielding metal arc and flux cored arc welding than during gas metal arc welding [8-9].

The spectrum of the arc is composed of a continuous background spectrum that follows the blackbody radiation law with the discrete lines superimposed on it. The shape of the discrete lines is modified by two major causes, namely collision line broadening and Doppler broadening [10]. Collision broadening is caused by the relatively high pressure (~ 1 bar) of the arc plasma. This pressure increases proportionally the probability of collisions between emitters and free electrons. In fact, it broadens the line width, because this is the quantum mechanical analogy of damping to a classical oscillator. Doppler broadening is caused by the very high temperature of the order of tens of thousand of kelvins of the arc plasma. This very high temperature increases the average speed of the atoms and therefore the Doppler shifts of the line emitted by particles that either move towards or away from the spectrophotometer are considerable [10].

Light radiation accompanies the arc welding process, and in most cases it can be observed directly, creating a hazard for the welder's eyes [4-9]. It may be also considered one of the signals emitted in the course of welding and utilized as a carrier of information about the welding process [10-15].

Measurements and the analysis of the arc light emission are used in investigations of the welding process, for example TIG [16]. During the investigations the following characteristics were specified: the temperature distribution in the arc, the temperature of the drops of the liquid metal, the amount of hydrogen in the gaseous shield of the welding arc and also the temperature of the weld pool. The investigations were also conducted to calculate the mean temperature of the welding arc [17]. The analysis of the arc light emission may help to develop the technique of taking photographs of the welding arc [18]. Investigations on the visible radiation of the MIG/MAG method also help to monitor the way in which the metal is transferred through the arc [12]. Optical methods also are applied to measure the length of the welding arc in the MIG/MAG [19, 20] and the TIG [11, 21]. This signal is much more sensitive to the changes of the welding conditions and should be used as a tool for monitoring of the TIG welding process [11].

Investigations which have been carried out so far cover the subject matter of utilization of the arc light radiation to monitor welding arc processes by the use of photodetectors [11, 19, 20]. The analysis of the spectrum of the radiation of the welding arc by a spectrograph are also available [22-24]. Unfortunately, the published results have been obtained in laboratory conditions [22-26] while on the industrial platform the spectral characteristics of the registered radiation are usually influenced by additional factors, *e.g.* paint, grease or rust on the surface of the welded material. The academic investigations were performed with great spectral resolution [22, 23, 25-28]. Such investigations are very valuable and give a lot of information on *e.g.* different ionization states of the ions observed in the welding arc plasma, but they cannot be performed in the real time monitoring process in a industrial plant. A modern method of the light spectrum analysis uses charge coupled devices (CCD) and gives information in a very short time (even less than ten milliseconds). The signal obtained from one CCD pixel gives the summarized output from many different spectral lines observed in the high resolution mode of the traditional measurement technique.

The main goal of the investigation presented in this paper is mathematical modeling of a single peak in spectral characteristics of light radiation emitted during the arc welding process and detected with the CCD device. This is the first step to design the new machine for monitor the welding process. Measurements and online analysis of spectral peaks allow to achieve a better accuracy of monitoring systems than up to now. Based on this premising assumption it should be possible to detect many different disturbances of the welding process, for example changes in the welding current, fluctuation of the arc length, disturbances of shielding gas flow, improper preparation of the joint, disturbances caused by a layer of paint, grease or rust, and many others.

2. Experimental setup

The tests have been performed on the stand (Fig.2) for automatic MAG welding operations equipped with a control consol. The testing plate for welding has been fixed while the welding head has been moved at controlled speed. The torch was located perpendicularly to the welding surface. All experiments were performed by bead-on-plate welding. The details of this industrial platform for MAG welding was given in [29]. The measuring system consisted of welding current (Hall sensor) and voltage transducers, a PC computer equipped with a CCD spectrophotometer card and a wire speed measurement device (described in [29]). The electrical signals from the current and voltage transducers have been recorded on the PC equipped with a NI DAQ 6036 measuring card. The analyzed radiation has been fed into the CCD spectrophotometer by means of standard fibre optics. A spectrophotometer card PCI 2000 ISA-A (Ocean Optics Inc.) has been used in this research. Its technical specification is given in Table 1. The spectral characteristics have been registered with the OII Base 32 program (Ocean Optics Inc.). Unfortunately, the manufacturer of the spectrophotometer card has not supplied the spectral characteristic of CCD sensitivity. The output of each pixel is converted to an electrical current which represents the amount of energy that has fallen on each pixel in a relative manner. Therefore, the author of this paper has estimated the spectral sensitivity of the used spectrophotometer card using a special measurement set up (Fig. 3). It has included: a halogen light source, a computerized monochromator SPM2 (Zeiss Jena), a picoammeter K485 (Keithley), a photodiode

S2387 (Hamamatsu), the spectrophotometer card PCI 2000 ISA-A, and a PC computer equipped with a GPIB card (National Instruments). LabView software has been used for data acquisition and control of the experiment.

Table 1. Data of spectrophotometer card PCI 2000 ISA-A.

Detector:	2048-element linear silicon CCD array
CCD elements:	2048 elements – 14 μm × 200 μm per element
Well depth (600 nm):	160 000 photons
Sensitivity (estimated):	86 photons/count 2.9 × 10^{-17} joule/count 2.9 × 10^{-17} watts/count 2.9 × 10^{-17} watts/count (for 1-second integration)
Detector range:	200-1100 nm
Useable range:	200-850 nm
Integration time:	3 milliseconds to 60 seconds (with 1 MHz A/D converter)

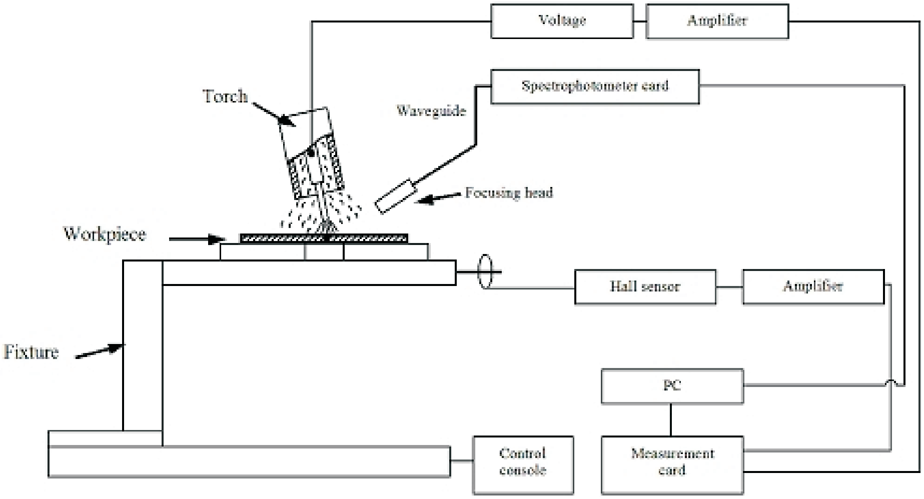

Fig. 2. Scheme of the experimental setup.

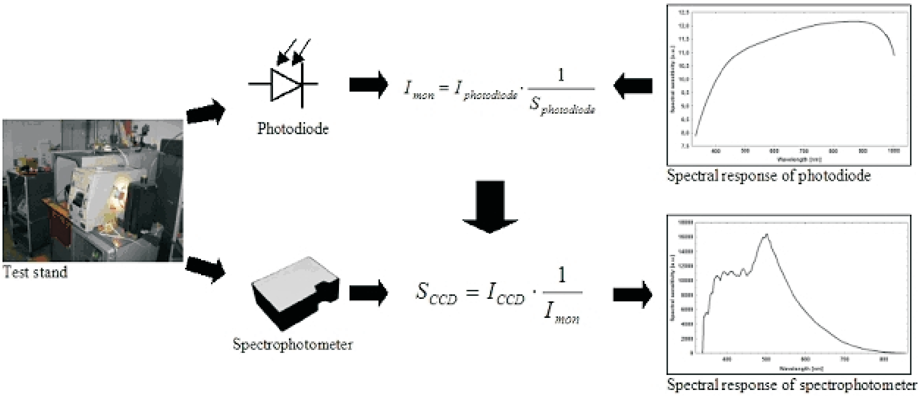

Fig. 3. Methodology to calculate the spectral response characteristic of the spectrophotometer card (I_{mon} – intensity of light from monochromator [photon/($m^2 \cdot$ s)], $I_{photodiode}$ – density of short-circuit current from the photodiode on the photosensitivity area of the photodiode, $S_{photodiode}$ – sensitivity of photodiode for the appropriate wavelength, I_{CCD} – intensity of light measured in relative units by the spectrophotometer card, S_{CCD} – sensitivity of spectrophotometer card for the appropriate wavelength).

The measurements of light intensity at the output of the monochromator have been performed for the same wavelengths using the photodiode and the spectrophotometer card. Using the spectral characteristics of Hamamatsu photodiode S2387, the intensity of light at the output of the monochromator was determined for different wavelengths (Fig. 3). Then the spectral dependence of the photosensitivity $S_{CCD}(\lambda)$ of the applied spectrophotometer card was calculated (Fig. 3).

Such determined $S_{CCD}(\lambda)$ has been used to estimate the intensity of light emitted in the arc welding process. Due to the different optical conditions of the experiments performed with the SPM2 monochromator and the arc welding process (*e.g.* the influence of the geometry of measurements at the welding stand, the apertures of the fibre optics, *etc.*), one should be rather careful in the analysis of the magnitude of the intensity of radiation emitted in the arc welding process. However, the photosensitivity of the used spectrophotometer card influences the spectrum of welding arc light emission (Fig.4).

It should be noted that the entire arc column has been treated as a point source of radiation. Though in academic investigations [23] the different parts of the cross section of the arc column are analysed as sources of the emitted light, in industrial applications and in monitoring (in real time) of the influence of disturbances of the welding process on the emitted radiation, the applied approach seems to be more practical and the only possible.

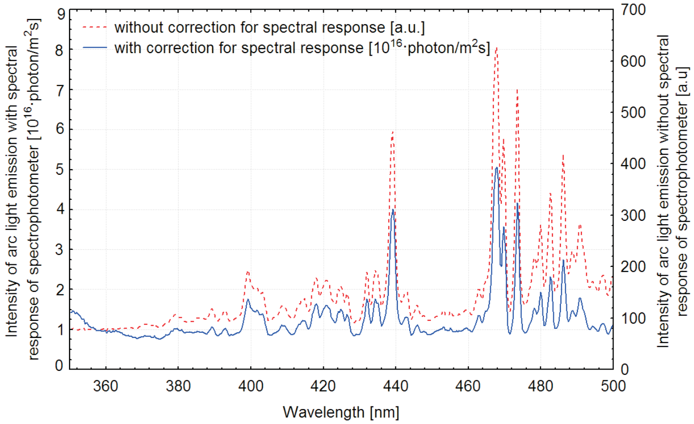

Fig. 4. Influence of sensitivity of spectrophotometer card on the results of measurement of spectrum arc light emission. I=104 A, U=16.5 V, 82% Ar + 18 % CO_2.

3. Results of the experiments

The purpose of the experiments was to find the influence of the welding current on the light emission during MAG welding. Mild steel S235 as the welding plate and the 1.2 mm diameter SG2 type welding wire were used. Experiments were performed on a clean plate with a shielding gas 82% Ar and 18 % CO_2, and by the application of welding parameters (Table 2) chosen experimentally to obtain a good shape of overlay welds (Fig. 5). The macroscopic examination of the cross section of overlay welds is shown in Fig. 6. Fig. 7 shows the influence of welding current intensity on the spectrum of light emitted from the welding arc.

Fig. 5. MAG beads made in the Ar + CO_2 shielding gas. A description of the welding parameters is given in Table 2 and in the text (Roman numbers represent different beads).

Table 2. MAG welding parameters for different samples (flow rate of the shielding gas – 14 l/min).

Bead d	Welding current I [A]	Arc voltage [V]	Welding speed [cm/min]	Heat input [kJ/cm]
I	104	16.5	27	4.8
II	130	18.0	30	6.5
III	189	21.1	35	11.0
IV	235	25.5	40	16.7

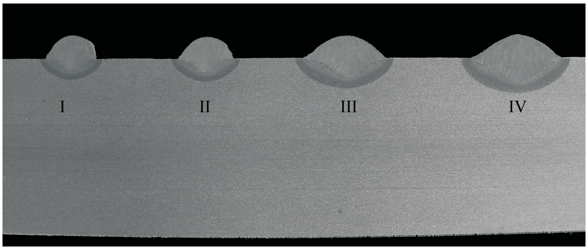

Fig. 6. Macroscopic examination of padding welds. Roman numbers represent different beads. The welding parameters are given in Table 2 (etching: Adler; magnification × 1).

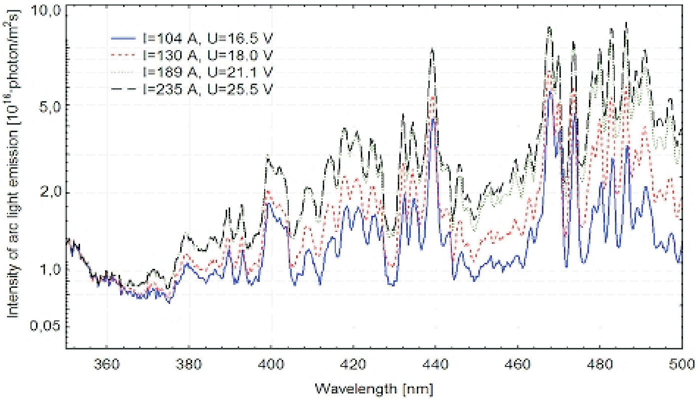

Fig. 7. Effect of the welding current on the arc light spectrum (description of the welding process in the text).

4. Fitting of the spectrum profile of welding arc light emission in the MAG process

The first step to design and build a MAG monitoring system based on arc light emission is to develop the methodology and procedures for identification and measurement of characteristic values of emission lines, for example: wavelength, width and intensity of the line or its profile. Intensity of light in separate emission lines is rather difficult to determine and it is very rarely discussed in contrary to the analysis of the relative intensities of different emission lines. The last procedure is presented in the next chapter. Firstly, the fitting of the spectral peaks in the spectra of light emitted during MAG welding is presented. The main goal of the first step is to find the best mathematical function to model the emission peak. One should remember that due to the low resolution of the spectrophotometer cards with limited number of CCD devices, the peak in a spectrum can be the envelope of a few separate emission lines.

First to calculate the centre and the width of the emission peak of a selected wavelength, fitting of different functions was performed. At the beginning the Gaussian function (Fig. 8) has been used

$$y = y_0 + Ae^{-\frac{2\ln 4\cdot(x-x_c)^2}{w_1^2}}, \qquad (1)$$

where A – amplitude, w – Full With at Half Maximum (FWHM), x_c – centre of wavelength, y_0 – additive constant.
The FWHM of the wavelength distribution can be calculated using the following relationship

$$w = \frac{w_1}{2\sqrt{\ln(4)}}. \qquad (2)$$

The second step was to fit the profile of emission peak by the Lorentz function (Fig. 8)

$$y = y_0 + \frac{2A}{\pi}\frac{w_1}{4(x-x_c)^2 + w_1^2}, \qquad (3)$$

where A, w_1, x_c and y_0 have the standard meanings.
The maximum value for the central wavelength can be expressed as

$$y_c = y_0 + \frac{2A}{w_1\cdot\pi}. \qquad (4)$$

The third step was to fit the profile by the Voight function (Fig. 8)

$$y = y_0 + A\frac{2\ln 2}{\pi^{3/2}}\frac{w_L}{w_G^2}\int_{-\infty}^{\infty}\frac{e^{-t^2}}{\left(\sqrt{\ln 2}\frac{w_L}{w_G}\right)^2 + \left(\sqrt{4\ln 2}\frac{x-x_c}{w_G} - t\right)^2}dt, \qquad (5)$$

where w_L, w_G – Lorentz and Gaussian FWHMs of emission peak, respectively. A, x_c and y_0 have the standard meanings.

The least square method and Levenberg-Marquardt algorithm has been used to fit the experimental data with functions (1), (3) and (5). The initial conditions for the fitting are given in Table 3. The same procedure for all emission lines has been carried out. Fig. 8 shows the comparison of the experimental profile for the peak at the wavelength of 439,28 nm with the fitted Gaussian, Lorentz and Voight functions. The experimental data have the best fitt with the Lorentz function (see Table 3 and Fig. 8). Similar results have been obtained from fitting of the 26 peaks of the arc light spectrum. Therefore the Lorentz function was chosen for the evaluation of the welding process on the basis of spectral characteristics of the emitted radiation.

Table 3. Initial and fitted values of parameters of different functions used in the fitting of one of the spectral peaks (see Figs. 7 and 8) registered using the CCD device during the welding of clean mild steel S 235 in the Ar + CO_2 shielding gas (χ^2 is the sum of the residuals in the least square fitting; I=104 A; U=16.5 V).

Parameter	Gaussian profile		Lorentz profile		Voight profile	
	Initial	Fitted	Initial	Fitted	Initial	Fitted
y_0	0	$1.17(9)\cdot10^{16}$	0	$6.59(86)\cdot10^{15}$	0	$98(34)\cdot10^{14}$
x_c	0	439.21(8)	5	439.28(2)	5	439.21(10)
w_1	1	0.75(4)	2	1.85(10)	–	–
A	10	$3.16(21)\cdot10^{16}$	1	$1.11(7)\cdot10^{17}$	1	$78(32)\cdot10^{15}$
w_L	–	–	–	–	1	$9(12)\cdot10^{-1}$
w_G	–	–	–	–	1	1.32(78)
χ^2	–	$2.63\cdot10^{30}$	–	$1.34\cdot10^{30}$	–	$3.29\cdot10^{30}$

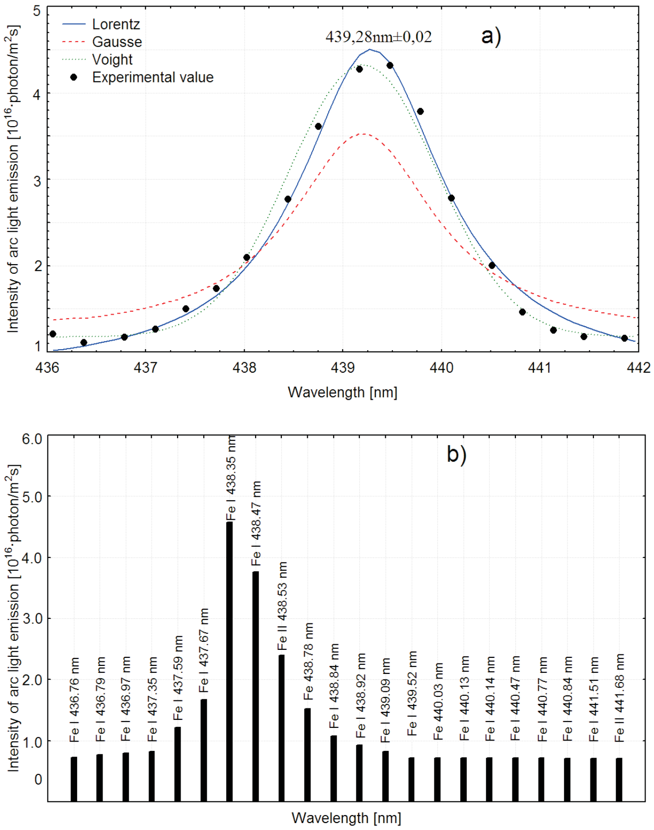

Fig. 8. Comparison of experimental data a) (●) with the best fitted: Gaussian, Lorentz and Voight functions for one of the spectral peaks (from Fig. 7) registered using the CCD device during the welding of clean mild steel S 235 in the Ar + CO_2 shielding gas (Values of the fitted parameters are given in Table 3; I=104 A; U=16.5 V), b) contribution to the observed spectral peak (only Fe and Fe I).

However, using the Lorentz function for fitting the peak in a spectrum, one should have in mind that it fact this function can be only interpreted as the best envelope of a few separate emission lines. Fig.8 presents one of the spectral peaks (from Fig. 7) registered using the CCD device during the welding of clean mild steel S235 (I=104 A; U=16.5 V, the other parameters of the welding process have been given in chapter 3). In Fig. 8 the emission lines that are probable for the investigated case are presented, too. The data have been taken from [30]. More likely the main contribution to the observed spectral peak presented in Fig. 8a is given by Fe I (Fig. 8b). However, the proof of this fact is very difficult. Fortunately, it seems to be not very important for using the low resolution spectral characteristics of radiation emitted in a welding process to monitor such a process.

5. Relationship between parameters describing spectral peaks of are light and parameters of welding process

Figure 9 shows the different influence of welding current intensity on the amplitudes, additive constants and widths (FWHM) of Lorentz functions that best fit the spectral peaks of arc light. It can be seen that the influence manifests itself in different ways in the case of different spectral peaks. Generally, the welding current intensity strongly influences the additive constants and amplitudes of the peaks in the spectral range from 480 nm to 500 nm. Fig.10 shows the dependence of the best fitted additive constants (used in (3)) on the intensity of the current in the welding process of clean mild steel S235 (I=104 A; U=16.5 V, the other parameters of the welding process have been given in chapter 3).

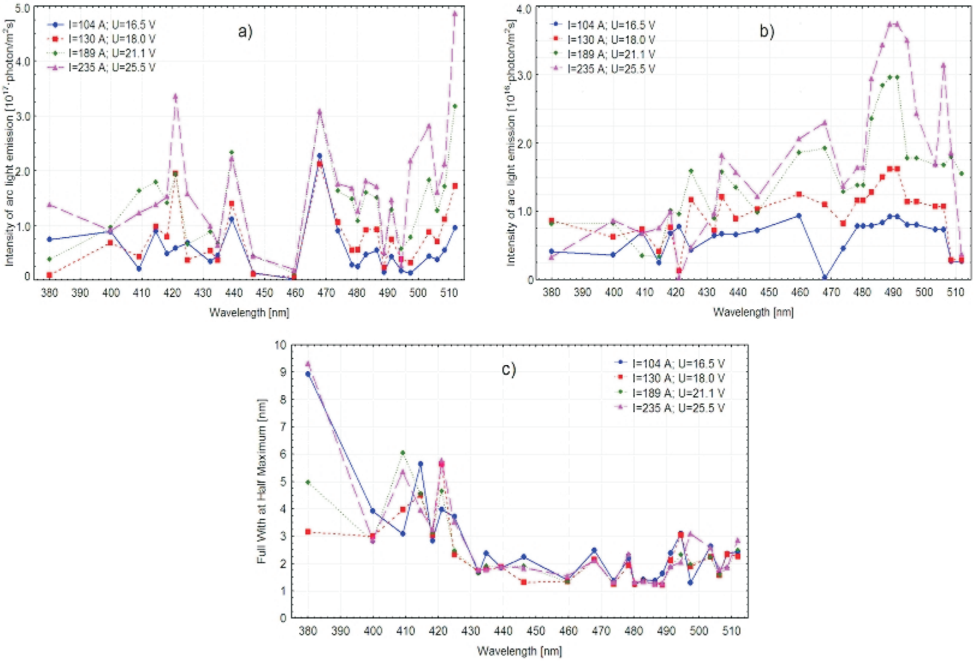

Fig. 9. Influence of welding current intensity on the amplitudes (a), the values (b) of additive constant in formula (3), and FWHM (c) of Lorentz functions that best fit the spectral peaks of arc light (other welding parameters from Table 2. Attention: curves presented in the figure cannot be interpolated).

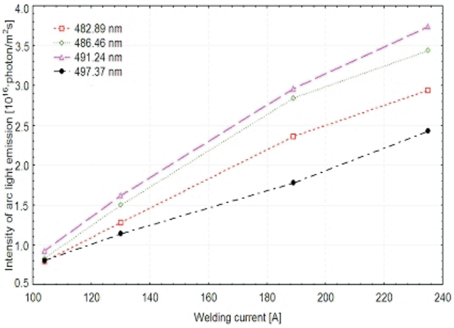

Fig. 10. Dependence of the best fitted additive constants (used in (3)) on the intensity of the current in the welding process of clean mild steel S 235 (I=104 A; U=16.5 V, the other parameters of the welding process have been stated in chapter 3). Different symbols represent values fitted to spectral peaks pinned to different wavelengths of radiation emitted during the welding.

Investigations have also been performed on the effect of imposed disturbances, in the form of paint or grease layers on the plate surface, on the intensity of MAG arc light radiation in the visible range. Mild steel S235 as the welding plate and 1.2 mm diameter SG2 type welding wire were used. Experiments were performed with the shielding gas 82% Ar and 18 % CO_2. The plate surface was clean, covered with oil paint or with machine grease. It was found that both the paint and grease layer influence the recorded spectral characteristics of MAG welding light radiation (Fig. 11). Fig. 12 presents the different influences of the existence of paint on the welded plate on the amplitudes, additive constants and widths of Lorentz functions that best fit the spectral peaks of arc light. It can be seen that the influence manifests itself in different ways in the case of different spectral peaks.

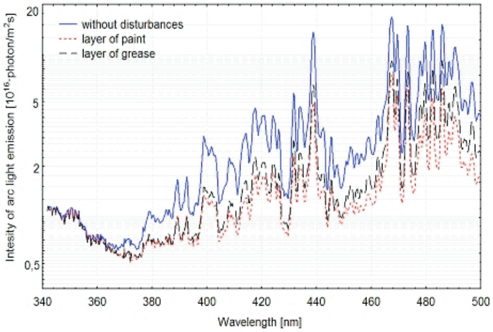

Fig. 11. The influence of disturbances on the MAG welding arc light spectrum (I=169 A, U=19.7 V , other parameters in the text).

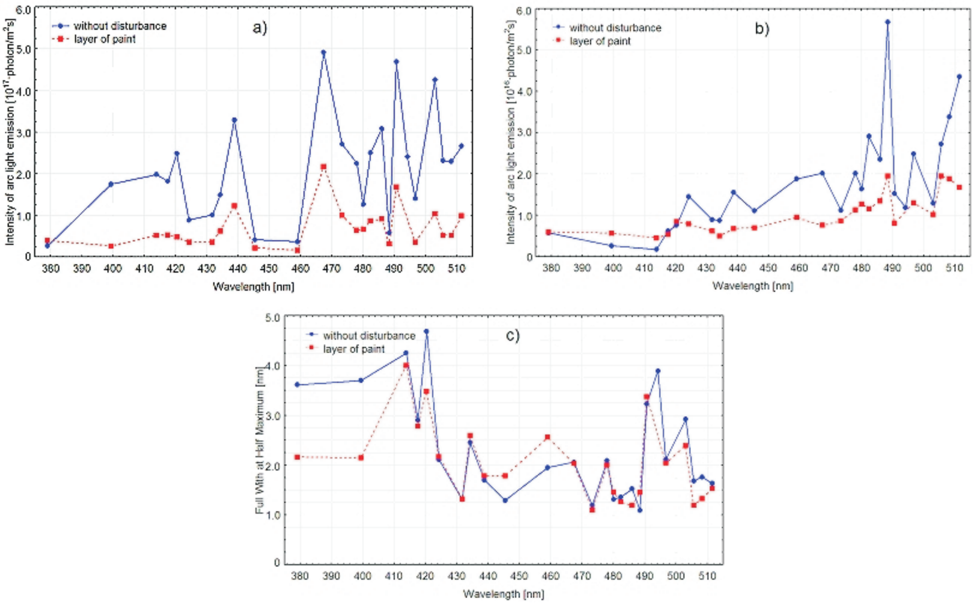

Fig. 12. Influence of paint on the welded plate on the amplitudes (a), the values (b) of additive constant in formula (3), and FWHM (c) of Lorentz functions that best fit the spectral peaks of arc light (welding parameters in text; Attention: curves presented in the figure cannot be interpolated).

6. Summary

Modern monitoring methods of welding processes are inherent in each automatics and robotics production system. These systems very rapidly detect any incorrectly made weld joints during manufacturing and in this way decrease the costs of production. That means the possibility of detecting any faulty parts without very costly nondestructive examinations. Very popular conventional monitoring methods of the welding processes utilized at present, based on measurements of the welding current and arc voltage, in many cases are inefficient and should be replaced and/or complete by nonconventional monitoring methods.

The presented investigations show that low-resolution spectral characteristics of arc light emission registered with a CCD device can be applied for the purpose of monitoring the welding process. The arranged measuring stand has made it possible to record the visible spectrum of the radiation of the welding arc within the range of wavelengths from 380 nm to 780 nm. The measuring stand comprised a spectrophotometer, a computer recording the results of measurements and a device for mechanized welding.

It was found that the spectral distribution of a single peak in the low resolution spectral characteristics can be best fitted with the Lorentz function. In the recorded spectrum of the welding arc light emission, separation of the ionic or atomic lines is not possible. However, the correlation between the parameters of the fitted Lorentz function and welding parameters (*i.e.* welding current) was obtained. The Lorentz function parameters depend also on the disturbances in the MAG welding process, *e.g.* their values are different in the cases of clean and painted surface of the welded mild steel S235 plate.

Results of the performed investigations show that the measurement of light radiation intensity during MAG welding can be used for the monitoring of the welding process quality. The experience gained during these investigations allows further research on the welding arc radiation phenomenon. The obtained knowledge increases the possibilities of using the signal for on-line monitoring of the welding process on automated and robotized stands. The analysis of the spectrum of the radiation of the welding arc should help to develop the new vision sensor in arc welding.

The investigations should be continued, and cover the following issues:

- utilize the artificial intelligence method to estimate the stability of the welding process,
- develop the filtering method, and methodology to signal analysis in time, and frequency domain,
- laser diagnostic on the welding arc in TIG and MIG/MAG methods,
- develop method of measurement of arc light emission in many points simultaneously.

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