ANALYSIS OF SPECTRUM OF THE WELDING ARC LIGHT FOR MONITORING OF ARC WELDING (Review)

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The state-of-the-art in research activities in the field of spectral analysis of light of the welding arc is reviewed. The effect of welding parameters on the spectrum of the welding arc light, spectral diagnostics of the arc plasma, automation of the welding process based on spectral analysis of the welding arc light, monitoring of the welding process, and automatic detection of defects in the welds are considered.

Keywords: *arc welding, weld, spectrum of the welding arc, spectral analysis, automation of welding, monitoring of welding, diagnostics of welded joint, weld defects*

The idea of using spectral analysis for automation and monitoring of arc welding consists in the fact that optical spectrum of the welding arc light can serve as a basis for generation of valuable information on the welding process, e.g. detection of deviations of welding parameters from the rated ones. Potentially defective regions in the welded joints can be determined from the above deviations. Real-time fixation of the deviations of the welding parameters will make it possible to adjust and correct the welding process to assure the required quality of the welded joints. Therefore, the spectral analysis can be used for both monitoring and automation of the welding process.

Technical implementation of the commercial spectral analysis-based systems for monitoring and automatic control of welding is made possible now owing to the use of the advanced digital spectrometers, which allow measurement of the optical spectrum within a few milliseconds.

The purpose of this article is to generalise investigations dedicated to the spectral analysis of light of the welding arc.

Much research has been made up to now in this field [1–16]. The following areas have received further development:

- investigation of the effect of welding parameters on the arc light spectrum;
- spectral diagnostics of the welding arc plasma;
- monitoring of the welding process by analysis of the arc light spectrum;
- automation of welding based on the spectral analysis of the welding arc light.

Investigations into the effect of welding parameters on the welding arc light spectrum are reported in studies [1–4]. The spectrum includes a continuous component, spectral lines of shielding and active gases, and spectral lines of metal of the parts welded.

Studies [1, 2] describe experimental investigations of the effect of the welding current on the intensity of spectral lines of metal and shielding gas in TIG welding. Spectra of the welding arc at different values of the current were measured during the welding process. Argon [1, 2] and helium [1] were used as a shielding gas. Plates of low-carbon steel, as well as stainless steel, copper, aluminium and titanium were used for welding. As shown by analysis of the obtained spectra, the intensity of spectral lines of metal and shielding gas increases with increase in the current during welding in argon atmosphere. This dependence is of a non-linear character. In welding of different metals in helium atmosphere the intensity of their lines either increases or decreases, or first increases and then decreases.

Study [2] was dedicated to investigation of the effect of filler wire feed speed on the spectrum of the welding arc light in TIG welding. The experiments were conducted by making welds on low-carbon steel plates and measuring spectra of the welding arc light in a range of 480–860 nm at different deviations of filler wire feed speed $v_{f.w}$ from the rated value corresponding to the technological standard. Decrease in the intensity of the arc light over the entire range of the measured spectrum frequencies was fixed at $v_{f.w}$ in excess of the rated value. The intensity of the light substantially increased in all regions of the spectrum within the measurement range with delay of feeding of the wire ($v_{f.w} = 0$).

The effect of length of the welding arc on the optical spectrum was investigated in study [3], wherein a mathematical model determining the dependence of the intensity of the welding arc light on the arc length and welding current was suggested. Integrated arc light intensity B_{iv} within the preset spectral range can be determined from the following formula:

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

where I is the welding current; L is the arc length; and G_i are the coefficients that depend on the specific welding conditions. As seen, in this formula the relationship between radiation intensity B_{iv} and arc length L is linear.

The experiments were carried out to check the adequacy of the model, in which the integrated arc light intensity was measured in a spectral range of 500–1000 nm in TIG welding of steel in argon atmosphere at different values of the arc length and welding current. Coefficients G_i were calculated on the basis of the experimental data. Comparison of the measured data with the B_{iv} values calculated by using the above model proved its adequacy for the arc length values ranging from 1 to 5 mm.

In study [4] the adequacy of mathematical model (1) was checked for a wider range of the welding currents (50–300 A). The model was proved to be adequate for values of the current ranging from 50 to 150 A. At the currents higher than 150 A the values of the intensity calculated by using the model were substantially different from the measured values.

The mathematical model was synthesised on the basis of an artificial neural network (ANN) of the «multilayer perceptron» type, allowing estimation of the welding arc length [4]. Two parameters served as the input data for ANN: welding current and intensity of light of the specified spectral line of argon atoms. The model was developed for the process of TIG welding of copper in argon atmosphere. Teaching of ANN was done by using the BPE (Back Propagation of Error) algorithm. Checking the neural network model with the experimental data showed its adequacy for the welding currents of 50–300 A and arc length of 2–5 mm.

Diagnostics of the welding arc plasma is a set of methods for measurement of parameters of the plasma that characterise its state. Study [5] suggested a method for diagnostics of the welding arc plasma based on its light spectrum. This method can be used to measure temperature of the plasma and concentration of its components (atoms, ions and electrons). The temperature and concentration were calculated by using the synthesised mathematical model of the multicomponent plasma. The mathematical model allows performing calculations for any chemical composition of the welding arc plasma.

An important task of monitoring of the welding process is fixation of regions of a welded joint characterised by the highest probability of formation of defects. The weld diagnostics method based on the spectral analysis provides for extraction of some diagnostic features from the welding arc spectrum, with the help of which it is possible to assess the quality of the welded joint.

Results of the experimental investigations aimed at development of procedures and systems for monitoring of the welding process on the basis of the spectral analysis of the welding arc light are given in studies [2, 6–13]. The following types of the diagnostic parameters have been identified up to now: integrated intensity of the light within the preset spectrum frequency band [6–8], spectral line intensity [2, 9], temperature of the welding arc plasma [8, 10, 11], root-mean-square value of the spectrum signal [10], and integrated parameters of profiles of the spectral lines [13].

The method for monitoring of the welding process suggested in patent [6] allows assessment of the quality of the welded joints by registering and analysing signals of the integrated intensity of light of the welding arc in several spectral lines. The intensities are measured by using photodetectors having the corresponding bandwidths. A decision on defectiveness of the weld is made by comparing the measured intensity signals and signals obtained for the reference welds with a normal structure.

Studies [7, 8] used values of the integrated intensity in several spectral bands as diagnostic features. As selection of the spectral bands is not a trivial problem, for this purpose the use was made of the automatic selection procedure based on experimental data. In that case the experimental data were two groups of spectra of the welding arc light. The first group was obtained for the welds with a normal structure, and the second — for welds containing defects.

The automatic selection was performed by using a specially developed algorithm based on the SFFS (Sequential Forward Floating Selection) algorithm. The experimental study showed the efficiency of the suggested procedure of selection of the diagnostic features for detection of defects forming as a result of oscillations of the welding current, variations in the arc length, non-uniform feeding of the shielding gas, and variations in width of the welding gap.

Study [8] describes the system developed for monitoring of the welding process, where a decision on the presence of defects is made by using the «multilayer perceptron» type ANN. Here the values of the intensity of a set of spectral bands selected by means of the above automation selection algorithm serve as a source of information for monitoring.

Studies [2, 9] suggested using the intensities of the spectral lines as diagnostic features. As established in study [2], the delay in feeding of a welding wire can be detected from a change in the intensity of argon spectral lines during the process of filler wire TIG welding. The system for monitoring of TIG welding of steel developed in study [9] uses signals of the intensities of the iron and hydrogen spectral lines for detection of defects in the welds. As shown by the experiments [9], the presence of tungsten inclusions and hydrogen in the weld metal, contamination of the metal surface with sand and non-uniformity of the shielding gas flow can be determined from a change in these signals.

The relationship between temperature of the welding arc plasma and quality of the welded joints was investigated in studies [8, 10, 11]. The temperature of the plasma was calculated from values of the intensity of several spectral lines of the shielding gas.

The experiments showed that by measuring the plasma temperature it is possible to detect such defects of the welds as burns-through and lacks of penetration, as well as the presence of the factors that have a negative effect on the quality of the welds (oscillations of the welding current, deflection of the welding torch from the joining line, and contamination of the metal surface with machine oil).

Study [10] suggested using the root-mean-square value of signal of the welding arc light spectrum as a diagnostic feature. The experiments showed that the value of this feature remains unchanged during the entire welding process at the absence of substantial deviation of the welding parameters from the rated ones. Formation of defects of the lack of penetration type is accompanied by decrease in the root-mean-square value, and in case of a burn-through there occurs a sudden change in this parameter. Marked fluctuations are fixed in the signal of the root-mean-square value in case of an edge displacement or deflection of the welding torch from the joining line.

In study [13] the spectral line profiles were approximated by the Lorentz function, and its parameters were used as diagnostic features to detect the perturbation actions appearing during the MAG welding process. Application of the integrated parameters of the spectral line profiles is explained by the fact that resolution of the fast-response digital spectrometers employed for real-time measurements is insufficiently high to fix the profiles of the individual lines located close to each other.

Because of averaging of the light intensity by discrete photosensitive elements of the spectrometer range, the digital signal of the spectrum comprises one wider intensity peak instead of several spectral lines. Such distortions cause decrease in the accuracy of measurement of the intensity of the individual spectral lines.

From this standpoint, the use of the integrated parameters of the spectral line profiles as diagnostic features is more preferable than the use of the intensity lines proper. The experiments proved that oscillations of the welding current, contamination of the metal surface in the welding location with paint and dirt can be detected from a change in the Lorentz function parameters.

The procedure was developed for identification of the metal transfer mode from the welding arc light spectrum in MIG/MAG welding [14] by the probability (Bayesian) decision-making technique. Statistical characteristics of the digital signal of the spectrum serve as primary parameters, on the basis of which the metal transfer mode is identified. According to the results of experimental verification of the procedure, the error in identification of the metal transfer mode was 5 %.

In plasma welding, the high-energy plasma flow makes a through hole in molten metal, which is immediately filled up. As a result, the through penetration weld is formed. To prevent burns-through and incomplete penetration of the welds, it is necessary to monitor the processes of appearance and disappearance of the through hole.

Study [15] describes the procedure developed for spectral analysis of the welding arc light, which can be used to detect the time points of appearance and disappearance of the through hole during the plasma welding process. Information on these time points is generated on the basis of analysis of variations in the intensity of the argon spectral lines.

The automatic seam guidance system was developed [3], compensating transverse deflections of the welding torch with respect to the longitudinally welded joint in TIG welding without groove preparation or with the V-groove. The source of information on deflections of the welding torch is a signal of the integrated intensity of the specified shielding gas spectral line. Oscillations of the intensity signal are fixed in movement along the joining line. Deflection of the welding torch from the joining line is calculated on the basis of the amplitude of oscillations of the intensity signal and values of time intervals between its local minima and maxima.

The team of German researchers and engineers developed a pilot sample of the system for automatic regulation of impulse MIG welding in argon atmosphere on the basis of the information on the welding arc light [16]. The system regulates input of the thermal energy to metal in each pulse of the welding current.

In impulse welding, the arc plasma temperature grows at a speed of several millions of Kelvin per second after the beginning of feeding of a pulse of the welding current. The pulse of the current is switched off when the arc plasma temperature reaches a certain value. The time point of switching off of the pulse is determined by measuring the integrated intensities of the arc light, I_m and I_g, in two corresponding spectral ranges Δ_m and Δ_g. The Δ_m range (approximately 260–550 nm) overlaps the region of the most intensive spectral lines of such metals as zinc, magnesium, aluminium, copper and iron, and the Δ_g range (approximately 650–950 nm) overlaps the region of the most intensive lines of the shielding gas (argon).

Arc light intensities I_m and I_g are measured by using two photodiodes. The difference of the measured intensities, $I_g - I_m$, monotonously decreases simultaneously with increase in the plasma temperature after switching on of the pulse of the welding current. After the $I_g - I_m$ difference decreases to the preset threshold corresponding to a certain maximal value of the plasma temperature, the regulation system feeds the control signal to switch off the pulse of the current. In the course of the tests the system developed provided stabilisation of the welding process at considerable deviations (±30 %) of the main and pulse currents from the rated values.

Therefore, at present the research and development efforts related to application of the spectral analysis for automation and monitoring of the welding process are at their initial stage. The suggested diagnostic features identified in spectrum of the welding arc light allow detection of defects in the welded joints and deviations of parameters of the welding process from the rated values. However, no investigations have been carried out as yet to confirm the high efficiency of the existing solutions required for their commercial application.

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NONDESTRUCTIVE TESTING OF WELDED JOINTS

IN-PROCESS QUALITY CONTROL OF WELDED PANELS OF ALLOY VT20 USING METHOD OF ELECTRON SHEAROGRAPHY

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Application of modern method of nondestructive testing (NDT), i.e. electron shearography, for VT20 alloy titanium panels, manufactured with preliminary elastic tension, is considered. The efficiency of application of NDT of titanium panel without dismantling of fixture for tension is shown, thus allowing the immediate elimination of defects, if required.

Keywords: *arc welding, welded panels, titanium alloy, quality control, in-process control, electron shearography*

The manufacture of welded metal structures, characterized by a low cost, high reliability and strength under different service conditions, is closely connected with the development of effective methods of NDT of their quality. One of the challenging methods of quality control is the electron shearography which is characterized by such advantages as a visualization, nocontact, high sensitivity, feasibility of real time conductance of investigations of objects of intricate geometric shape and large sizes. Comparative simplicity of this method allows it to be applied in the solution of complex problems, connected with analysis of deformations, quality control, etc. Using the electron shearography it is possible to determine deformations without numerical differentiation of data. Moreover, the method is not sensitive to vibrations, i.e. it can be used in different industry branches during in-process control of quality of structures, made of metallic and composite materials [1–5].