SPECTROSCOPY PEQULIARITIES OF THERMAL PLASMA WITH COPPER AND NICKEL VAPOURS

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Plasma of electric arc between Cu–Ni electrodes in the assumption of local thermodynamic equilibrium was investigated by optical emission spectroscopy. Temperature radial profiles in plasma column were obtained by Boltzmann plot techniques. Copper spectral lines were used to measure temperature distribution. Selection of Ni I spectral lines was carried out. Spectroscopic data of some optical transitions of nickel atom is testified.

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INTRODUCTION

The electric arc discharges take place often in the current interrupt devices of electric industry. This phenomenon causes the electric erosion of contact materials, which are widely used in production of such kind equipment. Nowadays, so-called “composite materials” are proposed to be used in fabrication of electrodes or contacts of switching devices. In addition, this type of materials is applicable in the sliding contacts of electric transport. The advantage of such materials is a combination of high erosion resistance, high thermal conductivity and electrical conductivity. Namely, the appropriate erosion properties of composition are due to high melting component in its content (e.g. tungsten, molybdenum or metal oxides) [1]. The good electrical and thermal conductivities are provided usually by low melting component (e.g. copper or silver). Such composite materials are fabricated typically by techniques of powder metallurgy [2, 3].

Obviously, development of contact composite materials can not be improved without careful examination of electric arc influence on working layers at electrode surface. It is naturally to study effects of arc plasma on erosion properties of such composites. Therefore one can be able to measure and control plasma parameters during such kind investigations.

Nowadays, electrical probes, microwave and laser diagnostics are widely used in laboratory plasma studies. Nevertheless optical spectroscopy (emission and/or absorption) is more preferred due to its non-perturbation contactless effect [4].

Plasma optical emission spectroscopy and laser absorption spectroscopy techniques were previously developed in diagnostics of free burning electric arc in air between composite Ag–CuO, Ag–SnO_2–ZnO and Cu–C electrodes [5 - 7]. The arc discharges of 3.5 or 30 A between the flat end surfaces of non-cooled rod electrodes in assumption of local thermodynamic equilibrium (LTE) in plasma were investigated. Such arcs can be used as model sources of real arc discharges in the current interrupt devices of electric industry.

The main aim of this paper is the development of optical emission spectroscopy techniques of electric arc plasma with copper and nickel vapours. Namely, within this study the selection of spectral lines of nickel atom and its spectroscopic data is carried out. So, it can be possible to investigate at the next steps the problem of interactions of arc plasma – composite Cu-Ni electrodes surface on the base of obtained in this research data.

1. EXPERIMENT

1.1. EXPERIMENTAL SETUP

The free burning electric arc was ignited in air between the end surfaces of the non-cooled electrodes. The discharge gap was 8 mm and the arc current was 3.5 A. Electrodes are positioned vertically: upper electrode – Ni (cathode), the bottom electrode – Cu (anode). Such type of arc is an initial model of electric discharge between composite Cu–Ni electrodes. Some reference data of copper and nickel one can find in Table 1.

In this work the diagnostic technique for simultaneous registration of spectral and spatial distribution of emission intensity of electric arc, which was previously developed [8], is used. Grating spectrometer and digital camera on charge-coupled device (CCD) base were used (Fig. 1).

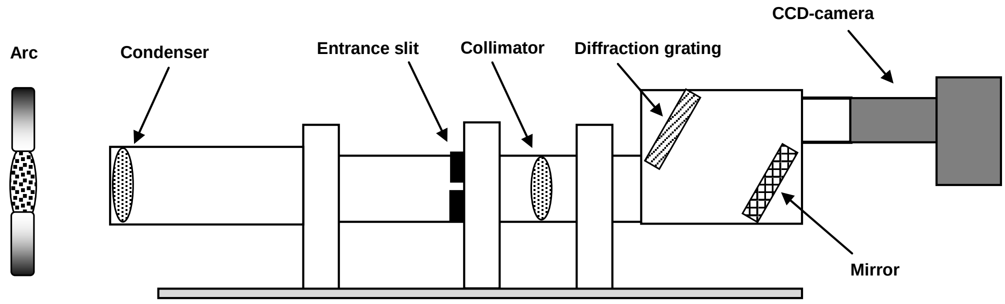

Fig. 1. Optical scheme of experimental setup [8]

The simultaneous registration of spatial intensity distribution in spectral range 400…660 nm is realized by optical scheme of experimental setup with diffraction grating 600 g/mm.

The additionally developed graphical user interface for treatment of obtained spectra images is able to realize the following functions [8]:

– interpretation of spectra;

– calibration of CCD-matrix spectral sensitivity by tungsten ribbon lamp;

– determination of spatial intensity distribution;

– transformation of observed intensity of radiation into its local values.

Because side-on (lateral) observation of plasma object was realized by developed experimental setup, it is necessary to use Abel inversion for obtaining of local values of intensity. The Bockasten technique for Abel inversion [9] was used in assumption of axial symmetry of investigated plasma source in graphical user interface as well [8].

1.2. EXPERIMENTAL PEQULIARITIES

The non-uniform spectral sensitivity of the CCD matrix was taken into account in the process of registration of plasma emission spectra of arc between such electrodes.

The most sensitivity of used matrix is in the range of wavelengths of 500…600 nm. To correct a non-uniform spectral sensitivity of the CCD matrix in the investigated wavelength range of 400…600 nm during experiments the etalon tungsten ribbon lamp was used (see section 1.1).

Table 1

Data of elements Cu I and Ni I. Part I

Element	Melting point, K (at normal pressure) [11]	Boiling point, K (at normal pressure) [11]	Thermal conductivity, $W/(m \cdot K)$ (at temperature 300 K) [11]	Electrical conductivity, $1/(Ohm \cdot m)$ (at temperature 300 K) [12]	Electronic configuration [13]	Ionization potential, eV [14, 15]
Copper	1356	2816	401	58.8	$3d^{10}4s^1$ (Cu I)	7.72
Nickel	1728	3073	91	14.7	$3d^84s^2$ (Ni I)	7.63

Table 2

Data of elements Cu I and Ni I. Part II

Element	λ, nm	Transition $i \rightarrow j$	g_j	g_i	E_j, eV	E_i, eV	$g_j f_{ji}$ [16]	$g_j f_{ji}$ [17]	$g_j f_{ji}$ [5]
Cu I	510.5	$3d^94s^2 \rightarrow 3d^{10}4p$	6	4	1.38	3.81	0.0312	0.02	0.0197
	515.3	$3d^{10}4p \rightarrow 3d^{10}4d$	2	4	3.78	6.19	0.96	1.9	1.6466
	521.8	$3d^{10}4p \rightarrow 3d^{10}4d$	4	6	3.81	6.19	1.84	2.4	1.9717
	570.0	$3d^94s^2 \rightarrow 3d^{10}4p$	4	4	1.64	3.81	0.0048	0.0069	0.0057
	578.2	$3d^94s^2 \rightarrow 3d^{10}4p$	4	2	1.64	3.78	0.01656	0.027	0.0130
Ni I	440.1	$3d^8(^3F)4s4p(^3P°) \rightarrow 3d^84s(^4F)5s$	9	11	3.19	6.00	1.17	6.8	–
	445.9	(3F)sp z5D→s4F)5s e5F	7	8	3.30	6.08	–	3.7	–
	503.5	$3d^9(^2D)4p \rightarrow 3d^9(^2D_{5/2})4d$	7	9	3.63	6.09	1.96	7.9	–
	508.4	$3d^9(^2D)4p \rightarrow 3d^9(^2D_{5/2})4d$	7	9	3.67	6.11	1.05	2.1	–
	547.6	$3d^{10} \rightarrow 3d^9(^2D)4p$	1	3	1.82	4.08	0.13	0.21	–

The non sufficient dynamical range of this kind of matrix is the additionally problem in spectra registration. The appropriate exposure time was chosen in every experiment to realize the optimal measurement of spectral line intensity. With this aim the neutral optical filters can be used as well.

1.3. MEASUREMENT TECHNIQUES

Optical emission spectroscopy is used in plasma diagnostics [10]. Plasma emission spectrum of the arc discharge between copper-nickel electrodes is shown in Fig. 2. Spectral lines of copper and nickel atom are well recognized in this spectrum. As soon as the selected for diagnostics spectral lines are not overlapped with the spectral lines of another plasma components it is possible to use them in the temperature determination by the Boltzmann's plot technique.

It must be noted that the recorded intensity of each spectral line is a result of the integration along the line of sight. To determine its local values the integral equation must be solved, which depends on the type of the distribution function of the local intensity values. As it was mentioned above, this problem has a solution in the case of axial symmetry of the distribution function of the local radiation intensity, and then the solution has the form of Abel's integral transformation [9]. To use this solution correctly each measurement was carefully examined from the point of view of axial symmetry of observed emission distribution. So, the radial plasma temperature distribution was determined by Boltzmann plot method under the assumption of LTE.

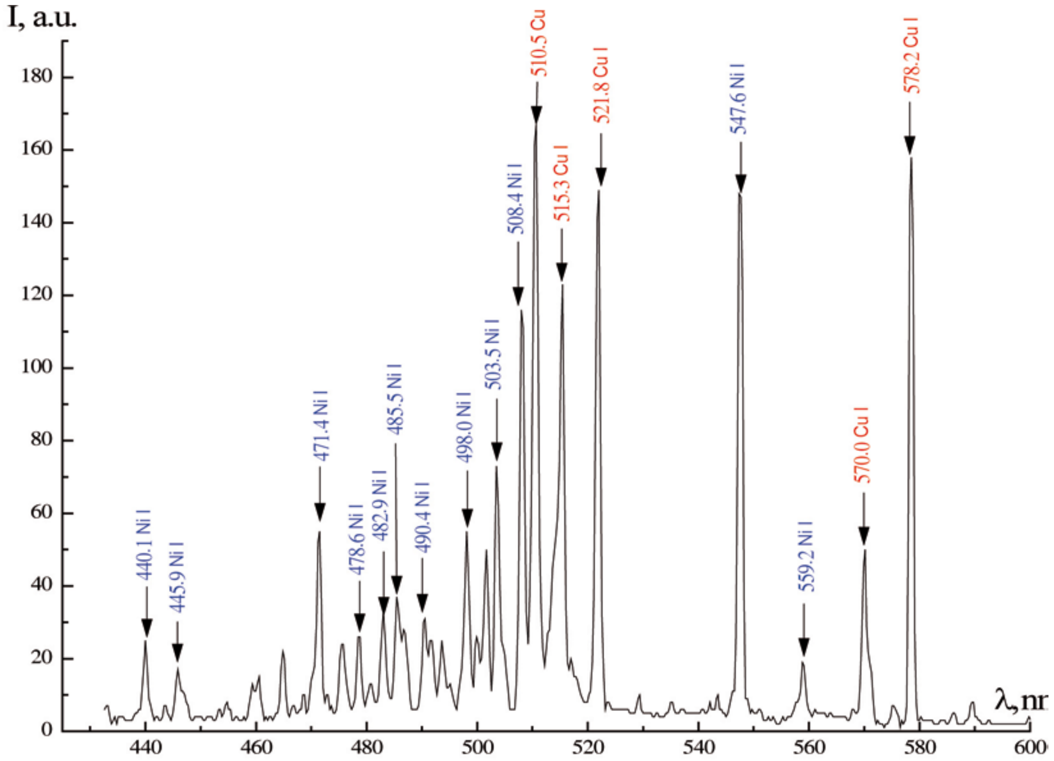

Fig. 2. Spectrum of electric arc between Cu-Ni electrodes

2. RESULTS AND DISCUSSIONS

It must be noted that plasma emission spectrum of electric arc between Cu-Ni electrodes, which is shown in Fig. 2, was obtained with taking into account of real CCD matrix sensitivity. So, intensities of Cu I and Ni I spectral lines can be used in measurements of plasma parameters.

Among the optical emission spectroscopy techniques, methods of relative intensities of spectral lines and Boltzmann plot are the most common for the plasma temperature determination.

For the application of these methods, first of all it is necessary to select "convenient" spectral lines for the diagnostics, which must satisfy certain requirements. Namely, these lines should be well isolated in the radiation spectrum and have suffcient intensity to their reliable registration. In addition, the difference between the excitation energy of the upper levels should be as large as possible to determine the temperature with a minimal error.

Spectral lines of copper atom Cu I 510.5, 515.3, 521.8, 570.0, 578.2 nm were chosen to measure radial profile of plasma temperature by Boltzmann's plot technique. Previously this method of diagnostics on the base of these lines was performed and corresponding spectroscopic data were recommended [18] in such thermal plasma spectroscopy (Table 2).

With the aim of validation of obtained results it is interesting to measure temperature of arc discharge plasma by both kind of spectral lines – copper and nickel atoms as well. Initially spectral lines Ni I 547.6, 508.4, 503.5, 445.9 and 440.1 nm were selected (see Table 2). Spectroscopic data, namely, oscillator strengths for these optical transitions one can find in [16] or [17]. It seems reasonable to find the most complete and comprehensive information about spectral lines of Ni I in NIST database [16]. Nevertheless, both of abovementioned sources of spectroscopic data must be carefully examined.

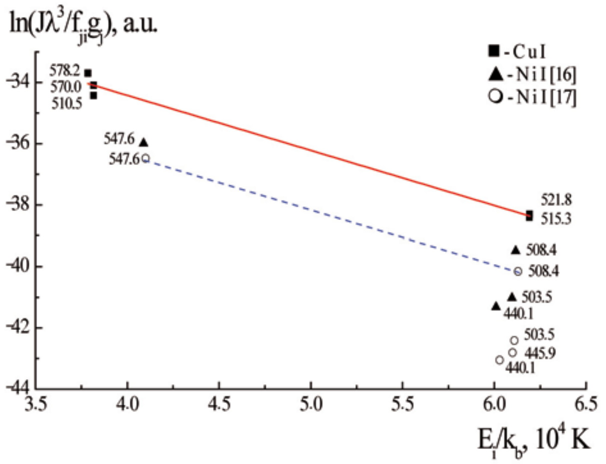

Fig. 3. Boltzmann plot involving of spectroscopic data for copper and nickel lines for the axial point of the average cross-section of plasma of free burning electric arc discharge between Cu-Ni electrodes at current 3.5 A

In Fig. 3 Boltzmann plot, involving of spectroscopic data for copper [5] and nickel [16 and 17] lines, for the axial point of the average cross-section of plasma of free burning electric arc discharge between Cu-Ni electrodes at current 3.5 A is shown. Two straight lines are drawn in this Figure, the slope of which corresponds to the temperature obtained by the Cu I spectral lines. This assumption can be able to use if plasma is in local thermodynamic equilibrium. So, both straight lines (solid line for copper and dashed line for nickel) must be defined by the same excitation temperature of thermal plasma in this point of discharge volume. Due to the uncertainty of the real ratio between the concentrations of atoms of nickel and copper it can not be possible to select spectroscopic data from sources [16] or [17] in the proper way. Therefore both of these spectroscopic data were used in measurements of the radial temperature profile.

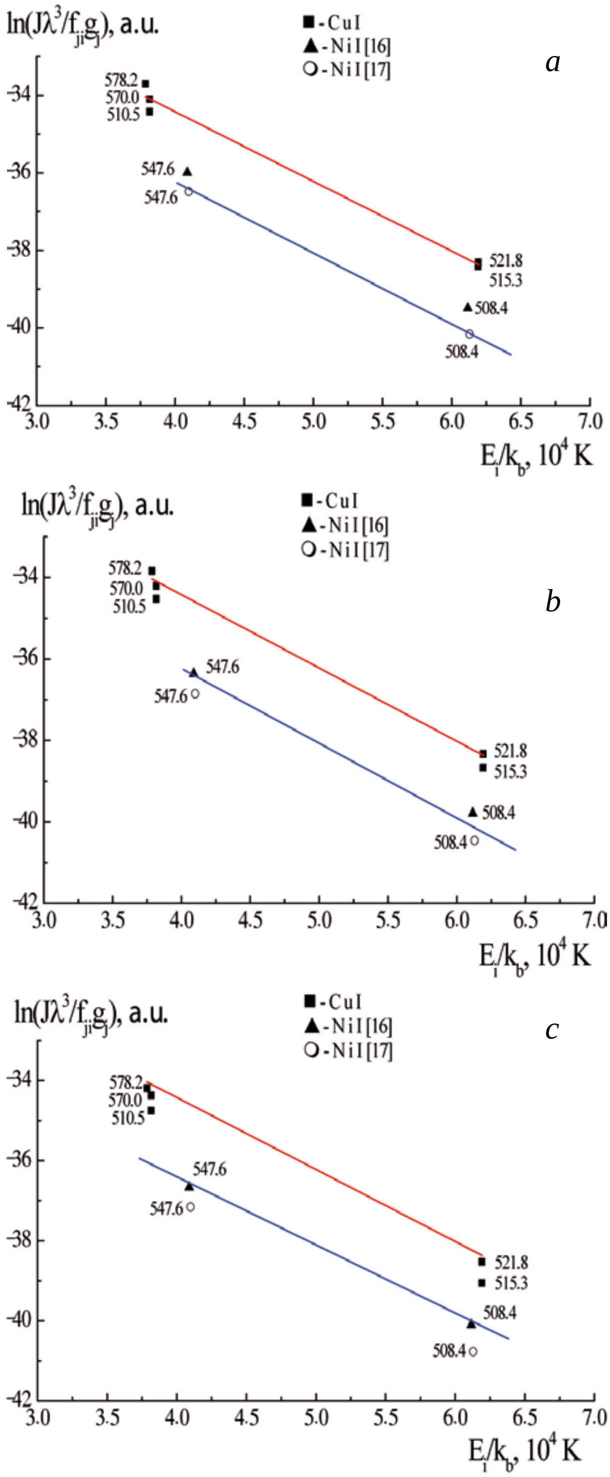

Fig. 4. Boltzmann plot involving of spectroscopic data for copper and nickel lines for the axial point (a) and radial distance 0.85 mm (b) and 1.81 mm (c) of the average cross-section of plasma of free burning electric arc discharge between Cu-Ni electrodes at current 3.5 A

Additional remark is concerned to the spectral lines Ni I 503.5, 445.9 and 440.1 nm. In real experiments with electric discharge at arc current 3.5 A the radiation intensities of these lines are not sufficient. Therefore, these lines should be removed from further consideration.

In Fig. 4 Boltzmann plots involving of spectroscopic data for copper and nickel lines for the axial point (see Fig. 4,a), and radial distance 0.85 mm (see Fig. 4,b), and 1.81 mm (see Fig. 4,c) of the average cross-section of plasma of free burning electric arc discharge are shown.

One can see that in plasma diagnostics only spectral lines Ni I 547.6 and 508.4 nm (for spectroscopic data [16, 17]) under these experimental conditions can be used. These lines are well isolated in the spectrum emission and have sufficient intensities. The difference between the energies of excitation of the upper levels is 2 eV.

So, to determine radial temperature distribution of plasma arc discharge between Cu-Ni electrodes spectral lines Ni I 547.6 and 508.4 nm (Fig. 5, curves 1, 2) and Cu I 510.5, 515.3, 521.8, 570.0, 578.2 nm (see Fig. 5, curve 3) were used. The radial temperature profiles obtained by Boltzmann plot method on the base of Cu I spectral lines (curve 3) and Ni I spectral lines (curve 2) with spectroscopic data [17] are coincide within measurement error.

The appropriateness of utilization in plasma diagnostics of spectroscopic data [16] is under discussion now. Therefore additional careful investigations by different techniques must be carried out to validate these data.

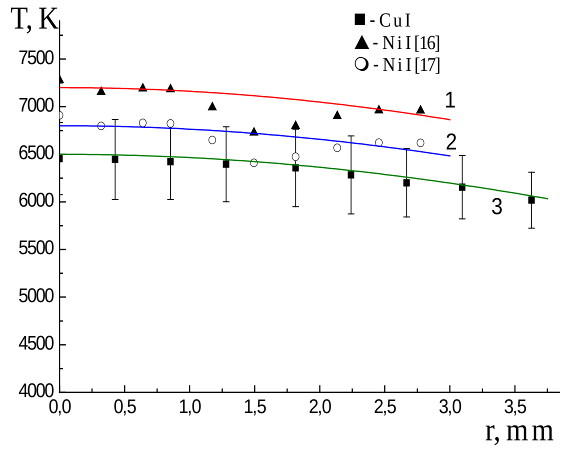

Fig. 5. Radial distribution of plasma temperature of electric arc discharge between Cu-Ni electrodes at current 3.5 A, obtained by Boltzmann plot method using Ni I (curve 1 and 2), Cu I (curve 3) spectral lines

CONCLUSIONS

Thermal plasma of electric arc discharge in air between Cu–Ni electrodes at arc current 3.5 A in the assumption of local thermodynamic equilibrium was investigated by optical emission spectroscopy. Nickel electrode was used as a cathode and copper was used as anode material. Such type of arc is developed as an initial model of electric discharge between composite Cu–Ni electrodes.

The radial profiles of temperature in discharge column were obtained by Boltzmann plot techniques. Copper spectral lines Cu I 510.5, 515.3, 521.8, 570.0, 578.2 nm were used to measure the radial distribution of plasma temperature. Selection of Ni I spectral lines for purposes of plasma diagnostics was carried out as well. Spectroscopic data of some optical transitions of nickel atom is testified at Boltzmann plot in some radial positions of arc plasma column.

Two spectral lines Ni I 547.6 and 508.4 nm of sufficient radiation intensities, which are well isolated in the spectrum emission, can be recommended in diagnostics of thermal plasma with nickel vapours. The difference between the energies of excitation of the upper levels is 2 eV. So, an appropriate accuracy of temperature measurement can be realized.

The additional investigations by different techniques must be carried out to validate the spectroscopic data of some optical transitions of nickel atom.

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ОСОБЕННОСТИ СПЕКТРОСКОПИИ ТЕРМИЧЕСКОЙ ПЛАЗМЫ С ПАРАМИ МЕДИ И НИКЕЛЯ

А.Н. Веклич, М.М. Клешич, В.В. Ващенко, И.А. Кузьминская

Методами оптической эмиссионной спектроскопии исследована плазма электродугового разряда между электродами Cu-Ni в предположении локального термодинамического равновесия. Методом диаграмм Больцмана получены радиальные профили температуры в плазменном столбе. Для определения распределения температуры использованы спектральные линии атома меди. Выполнена селекция спектральных линий Ni I. Для некоторых оптических переходов атома никеля выполнена экспериментальная проверка спектроскопических данных.

ОСОБЛИВОСТІ СПЕКТРОСКОПІЇ ТЕРМІЧНОЇ ПЛАЗМИ З ПАРАМИ МІДІ ТА НІКЕЛЮ

А.М. Веклич, М.М. Клешич, В.В. Ващенко, І.О. Кузьмінська

Методами оптичної емісійної спектроскопії досліджена плазма електродугового розряду між електродами Cu-Ni у припущенні локальної термодинамічної рівноваги. Методом діаграм Больцмана отримано радіальні розподіли температури в плазмовому стовпі. Для визначення радіального розподілу температури використано спектральні лінії атома міді. Виконана селекція спектральних ліній Ni I. Для деяких оптичних переходів атома нікелю виконана експериментальна перевірка спектроскопічних даних.