INVESTIGATION OF ELECTRIC ARC PLASMA BETWEEN COMPOSITE Cu–C ELECTRODES

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Plasma of electric arc discharge in air between composite Cu–C electrodes at arc current 3.5 A in the assumption of local thermodynamic equilibrium was investigated. Special electric device for arc ignition was suggested. The radial profiles of temperature in discharge column were obtained by optical emission spectroscopy. The radial profiles of copper density were obtained by laser absorption spectroscopy.

PACS: 52.70.-m, 84.30.Sk

INTRODUCTION

Nowadays, the electromotive vehicle using copper wire and various types of contacts that are attached to the surface of the pantograph [1]. During the movement of trains, electric arc between the wire and pantograph contacts often occurs, which significantly reduces the contact pair resource. The investigation of plasma properties of such electric arcs can be used for prolongation of the contact pair resource. In this study the model source of electric arc was used.

1. EXPERIMENTAL SETUP

1.1. MODEL SOURCE OF BREAKING ARC

Scheme of such source model is shown in Fig. 1. The arc plasma was ignited between the end surfaces of uncooled electrodes. The electromagnet with control scheme was used for arc breaking imitation and the direct synchronization with measurement circuits. Special electronic scheme (Fig. 2) for the electromagnet operation and control of the electric arc power source was developed. For electromagnet anchor retracting considerably higher voltage is required in comparison with its normal containment. This voltage is created by back–inverter and stored in the capacitor C9. The voltage retention is regulated by pulse width modulation. The bottom electrode can hit the top one during anchor electromagnet release. In order to avoid this effect voltage from the capacitor C10 is applied to the electromagnet coil while the upward movement of the electrode. This voltage was adjusted by pulse width modulation to achieve maximum damping effect.

The electrical circuit of the power supply of an electric arc is shown in Fig. 3. The XX3 plug provides connection to the control scheme (see Fig. 2).

1.2. EXPERIMENTAL TECHNIQUES

Copper-graphite composite is often used as a material for the sliding contacts of pantograph. That is why in this study copper-graphite electrodes with a copper content of 20% were used. The diameter of the electrodes was 6 mm, discharge gap was 8 mm. Discharge was operated at arc current 3.5 A.

At the first stage, parameters of stationary plasma were investigated. The complex of this study includes two independent techniques: optical emission spectroscopy (OES) and laser absorption spectroscopy (LAS). Experimental setup for the OES is shown in Fig. 4. The middle cross-section of the image of an electric arc projected on the entrance slit of the diffraction spectrometer (600 lines/mm) by condenser lens. The spectrum was recorded by CCD camera [2].

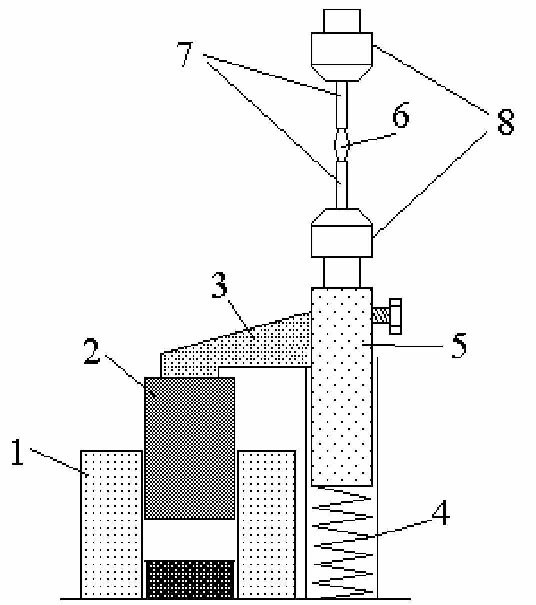

Fig. 1. Scheme of the electrode unit. 1 – coil electromagnet; 2 – anchor; 3 – arm; 4 – spring; 5 – mandrel holder electrode; 6 – electric arc; 7 – electrodes; 8 – electrodes mandrels collet clamps

Experimental setup for the LAS is shown in Fig. 5. Emission radiation of copper vapor laser, passed through the arc discharge plasma, was recorded by CCD matrix [3]. Due to the presence of copper in such multicomponent plasma, the main mechanism, which is responsible for reducing the intensity of the laser radiation, is resonant absorption by copper atoms. Therefore, by measuring of the spatial distribution of the plasma optical thickness, the appropriate distribution of copper atom concentration can be determined.

2. RESULTS AND DISCUSSION

The optical emission spectroscopy was carried out at the initial stage of this study. Emission spectrum of the plasma arc discharge between copper-graphite electrodes is shown in Fig. 6. Spectral lines of the copper 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.

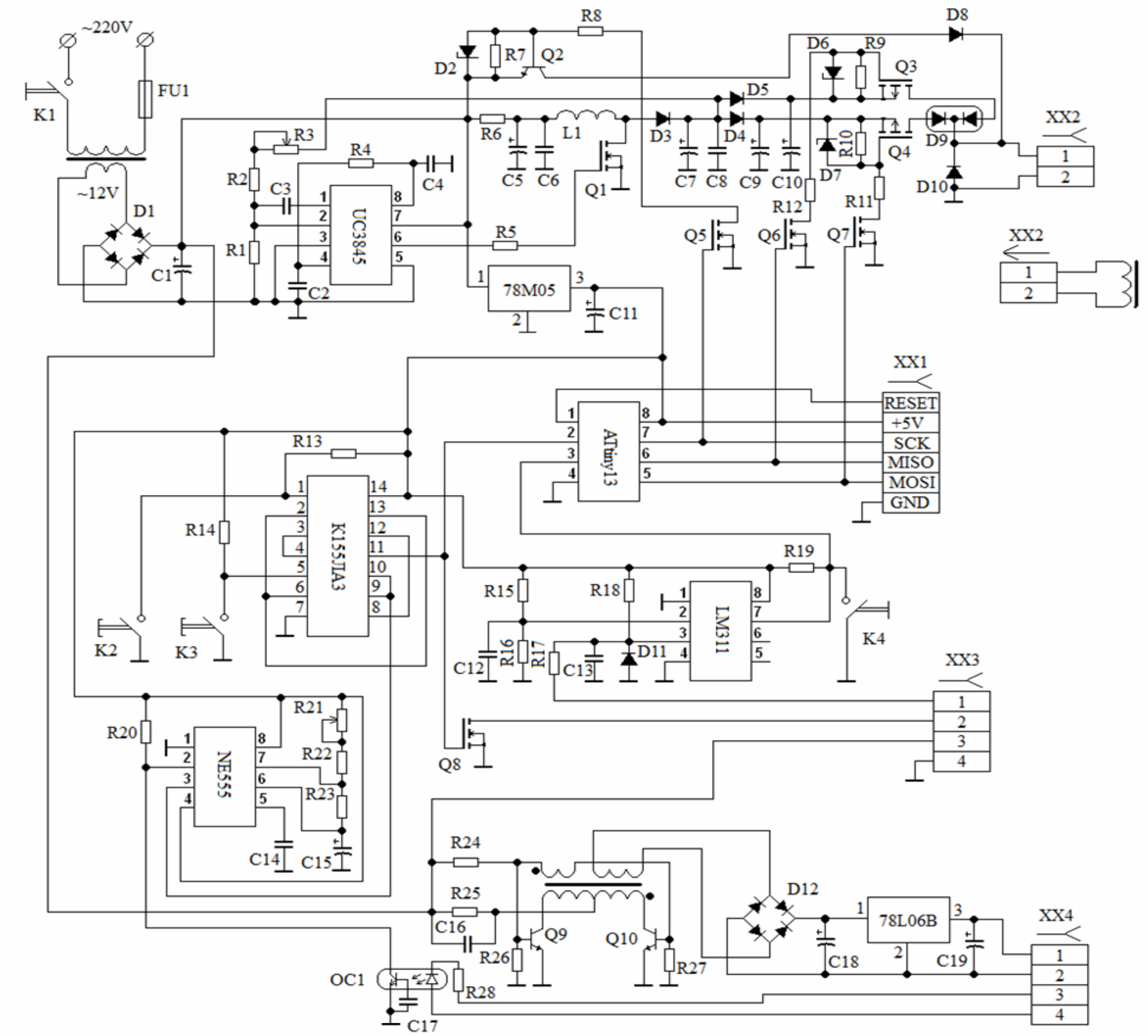

Fig. 2. The electric circuit of the electromagnet control. XX1 – internal connector for the microcontroller programming, XX2 – electromagnet connector, XX3 – connector to the power supply of electric arc, XX4 – input synchronization

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. 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 [4]. 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 the Boltzmann plot method under the assumption of local thermodynamic equilibrium (Fig. 7). Copper atom spectral lines 510.5; 515.3; 521.8; 570.0 and 578.2 nm and appropriate spectroscopic constants taken from [5] were used in this case. This radial distribution was compared with the plasma temperature distribution [6] in arc discharge between copper electrodes under the same experimental conditions. As one can see from the Fig. 7 radial distributions of temperature are almost the same for both types of electrodes.

Therefore, we can summarize that the copper content in plasma of such discharges is comparable.

Copper vapor laser "Kriostat 1" was used in the laser absorption spectroscopy. There are two spectral lines 510.5 and 578.2 nm in its generation spectrum. Additional diffraction grating was used [3] to select 510.5 nm line, which corresponds to the transition $4p\ ^2P_{3/2}$ (3.817 eV) → $4s^2\ ^2D_{5/2}$ (1,389 eV).

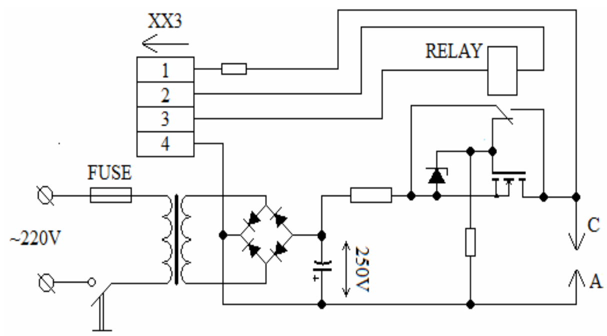

Fig. 3. The electrical circuit of the power supply electric arc plasma. C – cathode, A – anode

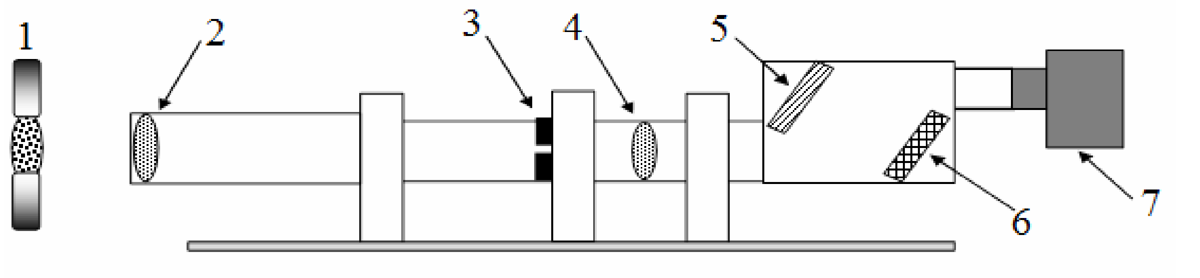

Fig. 4. Experimental setup for optical emission spectroscopy of plasma.
1 – arc; 2 – condenser lens; 3 – input slit; 4 – collimator; 5 – diffraction grating; 6 – mirror; 7 – CCD camera

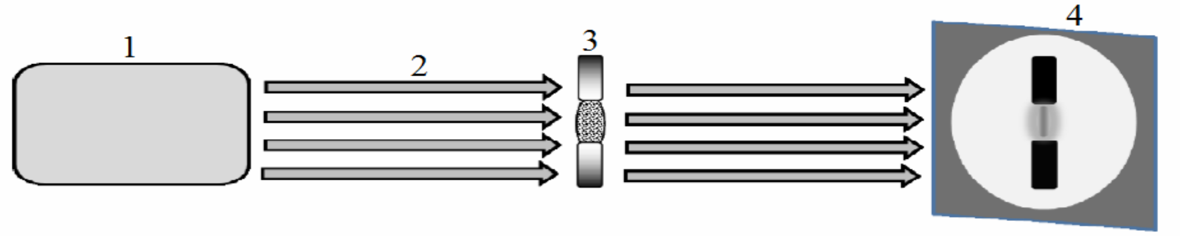

Fig. 5. Experimental setup for laser absorption spectroscopy of plasma.
1 – copper vapor laser "Kriostat 1"; 2 – laser radiation; 3 – arc; 4 – CCD matrix

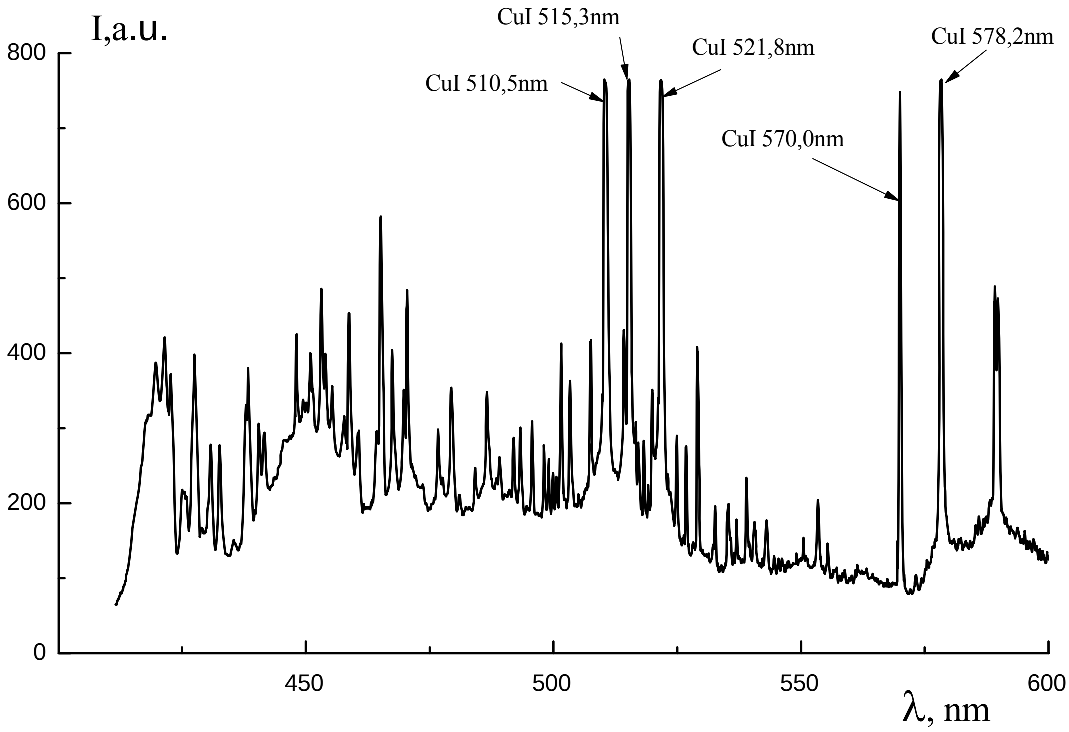

Fig. 6. The emission spectrum of the plasma arc discharge between copper–graphite electrodes

As one can see from Fig. 6 this spectral line is well isolated from others. Since the divergence of the laser radiation is small, it was an opportunity to place the CCD matrix at a distance from the electric arc sufficient to neglect by own plasma emission. The plasma optical thickness is defined as follows:

$$\tau(\lambda_0, x) = \ln\left(I_1(\lambda_0, x)/I_2(\lambda_0, x)\right) \qquad (1)$$

where, I_1, I_2 – the intensity of the probing and absorbed radiation respectively, x – coordinate perpendicular to the direction of the laser beam. As far as half width of laser spectral line is more narrower than absorption line of plasma, so it can be assumed as absorption in the center of spectral line. Therefore experimentally obtained optical thickness correspond to the absorption at the center ($\lambda=\lambda_0$) of the spectral line. Under the assumption of axial symmetry of the plasma object one can obtain the radial distribution of absorption coefficient $\kappa(\lambda_0,r)$ using Abel integral equation [4].

The absorption coefficient $\kappa(\lambda_0,r)$ depends on the number of absorbing centers (in this case copper atoms, that are at the $4s^2\ ^2D_{5/2}$ level). Relation between the local values of the absorption coefficient and level population is [1]:

$$\int_0^\infty \frac{1}{\lambda^2}\kappa(\lambda,r)d\lambda = \frac{\pi e^2}{m_0 c^2}\cdot f_{ki}\cdot N_k(r)\cdot\left(1-\frac{g_k N_i(r)}{g_i N_k(r)}\right), \qquad (2)$$

where N_i – population of the upper level ($4p\ ^2P_{3/2}$), N_k – population of the lower level ($4s^2\ ^2D_{5/2}$), f_{ki} – oscillator strength, g_k, g_i – statistical weights of levels, λ – wavelength, m_0, e – mass and charge of an electron, c – speed of light. To link the integral in expression (1) with the experimentally measured absorption coefficient at the center of the spectral line, one must know the shape of its contour. Since the broadening of this line in the above discharge type caused by Doppler mechanism, we consider Gaussian line contour:

$$\kappa(\lambda,r)=\kappa(\lambda_0,r)\cdot\exp\left(-\frac{\mu\cdot c^2}{2RT(r)}\cdot\left(\frac{\lambda_0-\lambda}{\lambda}\right)^2\right), \qquad (3)$$

where, μ – molar mass of atoms, R – universal gas constant, $T(r)$ – radial temperature distribution. Then, the integral can be written as:

$$\int_0^\infty \frac{1}{\lambda^2}\kappa(\lambda,r)d\lambda=\kappa(\lambda_0,r)\cdot\frac{\lambda_0}{c}\sqrt{\frac{2\pi RT(r)}{\mu}}. \qquad (4)$$

In our case, the terms $\frac{g_k N_i(r)}{g_i N_k(r)}$ in the expression (1) can be neglected. Then, the population of the lower level ($4s^2\,{}^2D_{5/2}$) has the form:

$$N_k(r)=\kappa(\lambda_0,r)\cdot\frac{\lambda_0 m_0 c}{e^2 f_{ki}}\sqrt{\frac{2RT(r)}{\pi\mu}}. \qquad (5)$$

Therefore, knowing the absorption coefficient we can determine the spatial distribution of the corresponding level population.

Radial distribution of the absorption coefficient and $4s^2\,{}^2D_{5/2}$ level population for copper-graphite electrodes are shown in Fig. 8. In addition, the distribution of the same level population for the discharge between copper electrodes under the same experimental conditions [3] is shown in Fig. 8.

Radial distribution of the copper atoms concentration can be obtained from the Boltzmann distribution in the local thermodynamic equilibrium (LTE) assumption:

$$N_{Cu}(r)=N_k(r)\frac{U(T(r))}{g_k}\exp\left(\frac{E_k}{kT(r)}\right), \qquad (6)$$

where E_k and g_k energy and the statistical weight of level $4s^2\,{}^2D_{5/2}$, $U(T)$ – partition function of the copper atom:

$$U(T)=\sum_i g_i\exp\left(\frac{E_i}{kT}\right). \qquad (7)$$

Radial distributions of the copper atoms concentration in the plasma for copper-graphite and copper electrodes are shown in Fig. 9. Values for the discharge between copper electrodes were taken from [3] under the same experimental conditions.

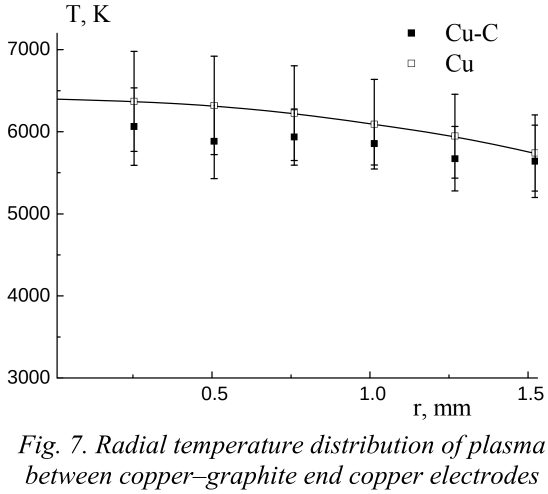

Fig. 7. Radial temperature distribution of plasma between copper–graphite end copper electrodes

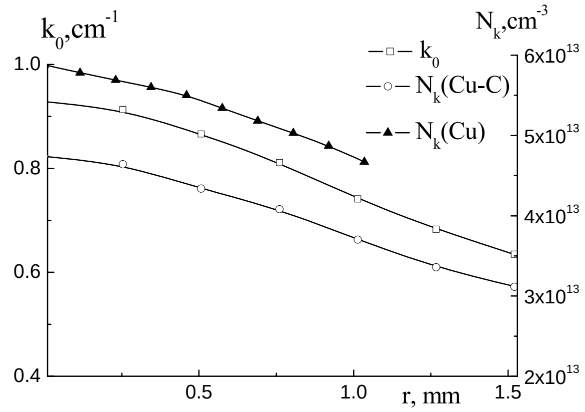

Fig. 8. Radial distribution of κ(λ_0) *and* N_k *in the arc discharge plasma between composite Cu-C and copper [3] electrodes*

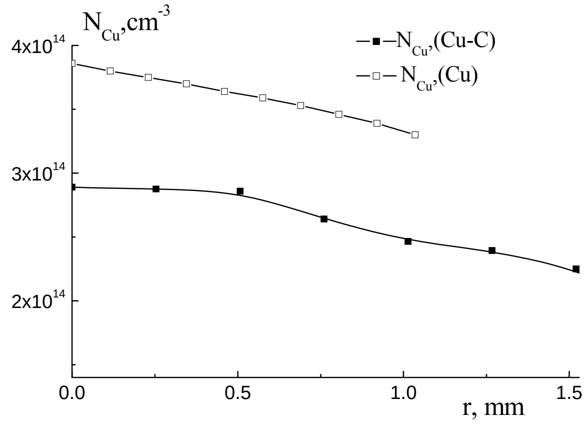

Fig. 9. Radial distribution of the copper atom concentration in the middle cross section of the arc discharge between copper-graphite and copper [3] electrodes

Fig. 7 shows that the plasma temperature for copper-graphite and copper electrodes are almost identical. This is the interesting result taking into account that the mass fraction of copper in copper-graphite electrodes is 20%. This result directly indicates that the plasma parameters for copper–graphite electrodes are mainly determined by copper component. Indeed, the simple analysis of the distribution of the copper atoms concentration in Fig. 9 displays that they are almost the same for copper and copper-graphite electrodes. This can be explained by the considerable difference in the ionization potential for copper (7.72 eV) and carbon (11.25 eV). In addition, almost identical copper component concentration in plasma arc between copper and copper-graphite electrodes indicates about approximately the same erosion of copper in this electrodes. One can conclude the possible realization of the formation of copper islands on the electrode surfaces, to which arc "tieds". However, this assumption can be finally clarified by additional metallographic studies [7, 8].

CONCLUSIONS

Model plasma source unit with real breaking arc was developed for the simulation of discharges which occurred during sliding of Cu-C composite electrodes on copper wire at electromotive vehicles. The electromagnet was used for arc breaking. Microcontroller control system allows damping of moving part oscillations and synchronization with measurement circuits.

It was found, that radial profiles of temperature and copper atoms concentration obtained for Cu-C composite electrodes in stationary mode of electric arc are comparable with results for discharge between copper electrodes. So, one can conclude, that properties of arc discharge between composite Cu-C electrodes are mainly determined by copper impurity. Therefore, assumption of possible formation of copper islands on the investigated electrodes' surface is suggested.

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Article received 16.05.2013

ИССЛЕДОВАНИЕ ПЛАЗМЫ ЭЛЕКТРОДУГОВОГО РАЗРЯДА МЕЖДУ КОМПОЗИТНЫМИ Cu–C-ЭЛЕКТРОДАМИ

А.Н. Веклич, В.Ф. Борецкий, А.И. Иванисик, А.В. Лебедь, С.А. Фесенко

Исследовали плазму электродугового разряда между композитными Cu–C-электродами при силе тока дуги 3,5 А в предположении локального термодинамического равновесия. Предложено специальное электронное устройство для инициации дугового разряда. Радиальные распределения температуры в разрядном промежутке получены с использованием оптической эмиссионной спектроскопии. Радиальные распределения концентрации атомов меди получены с помощью лазерной абсорбционной спектроскопии.

ДОСЛІДЖЕННЯ ПЛАЗМИ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ МІЖ КОМПОЗИТНИМИ Cu––C-ЕЛЕКТРОДАМИ

А.М. Веклич, В.Ф. Борецький, А.І. Іванісік, А.В. Лебідь, С.О. Фесенко

Досліджували плазму електродугового розряду між композитними Cu–C-електродами при силі струму дуги 3,5 А у припущенні локальної термодинамічної рівноваги. Запропоновано спеціальний електронний пристрій для ініціації дугового розряду. Радіальні розподіли температури в розрядному проміжку отримані за допомогою оптичної емісійної спектроскопії. Радіальні розподіли концентрації атомів міді отримані за допомогою лазерної абсорбційної спектроскопії.