THERMAL PLASMA OF ELECTRIC ARC DISCHARGE IN AIR BETWEEN COMPOSITE Cu-C ELECTRODES

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The complex technique of plasma property studies is suggested. As the first step the radial profiles of temperature and electron density in plasma of free burning electric arc discharge in air between Cu-C composite and brass electrodes, as well as copper electrodes in air flow, were measured by optical emission spectroscopy techniques. As the next step the radial profiles of electric conductivity of plasma mixture were calculated by solution of energy balance equation. The electron density is obtained from electric conductivity by calculation in assumption of local thermodynamical equilibrium in plasma.

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INTRODUCTION

Usually copper wire and various types of inserts, which are fixed on the contact surface of the pantograph, are widely used in power supply circuits of electric transport. Graphite, coke, copper-graphite composite or copper alloys can be used as materials in producing of such inserts. Each of these types of inserts has some advantages and disadvantages [1]. In particular, in spite of good lubricating properties of graphite and coke inserts, they have a comparatively high electrical resistivity. So, the deterioration of friction parameters of copper trolley wire takes place due to annealing in a result of significant Joule heating. Therefore graphite is mixed with copper powder to reduce of resistivity. The content of copper in such composite inserts is insignificant according to tribology demand.

The aim of this work is a study of plasma properties of model electric arc ignited in air atmosphere between Cu-C composite or copper electrodes. This paper deals with experimental investigations of parameters of thermal plasma mixture and calculations of electrical conductivity as well as electron density in discharge column.

1. EXPERIMENTAL INVESTIGATIONS

1.1. ARC DISCHARGE ARRANGEMENT

The free burning electric arc was ignited in air between the end surfaces of Cu-C composite non-cooled vertically arranged electrodes. At the fabrication technology copper content in this composition was around 20 %. This copper content was additionally verified by mass spectrometry studies. The peculiarities of surface condition and erosion rate of composite electrodes under influence of arc discharge and plasma composition as well are not studied in detail yet. Nevertheless, it was strongly verified that both electrodes were not significantly consumed during experimental investigations.

Additionally arc discharge between non-cooled copper electrodes in air flow 6.4 slpm and arc in air between brass electrodes were studied.

The diameter of the rod electrodes was 6 mm, the discharge gap was 8 mm and arc current was 3.5 or 30 A. To avoid the metal droplet appearing a pulsing high current mode was used: namely, the rectangular current pulse of 30 A was put on the "duty" low-current (3.5 A) discharge. The high-current pulse duration was of 30 ms. The registration of arc plasma radiation was performed at 7 ms after current pulse rise when a steady-state mode of electric arc discharge was realized. We found in our previous investigation that in such steady-state mode of arc discharge in air between copper containing electrodes the local thermodynamical equilibrium (LTE) is realized [2].

A more detail description of experimental setup and measurement procedure are presented in [3, 4].

1.2. TEMPERATURE MEASUREMENTS

Plasma temperatures were obtained by Boltzmann plot method. This method and experimental setup are described in detail in [4].

The examples of radial temperature profiles of electric arc plasma one can find in [5] – for composite Cu-C electrodes at arc current 3.5 A; [6] – for copper electrodes in air flow at arc current 3.5 A and 30 A; [3] – for brass electrodes in air at arc current 3.5 A. Experimentally obtained data of radial temperature distribution was approximated by Gaussian. Both upper (T_{Sup}) and bottom (T_{Inf}) error bars of temperature were approximated by Gaussian also.

1.3. ELECTRON DENSITY MEASUREMENTS

Electron densities were obtained from half-width of spectral line Cu I 515.3 nm in assumption of dominating quadratic Stark effect at 30 A. The spectral device combined with Fabry-Perot interferometer in etalon mode was used for registration of spectral line profiles [7]. The examples of radial electron density distributions of electric arc plasma one can find in: [6] – for copper electrodes in air flow at arc current 3.5 A and 30 A: [3] – for brass electrodes in air at arc current 3.5 A.

2. PLASMA PARAMETERS CALCULATION

2.1. TRANSPORT PROPERTIES OF ARC DISCHARGE PLASMA

The radial profiles of thermal and electrical conductivity of air-copper plasma mixtures were calculated in detail in our previous investigation [8]. Plasma of electric arc between copper electrodes in air flow at current 3.5 A was studied.

The electrical conductivity σ of air plasma with admixing of copper can be calculated by solution of energy balance equation:

$$\sigma E^2 + \frac{1}{r}\left[\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right)\right] = 0. \qquad (1)$$

It was found [8] that the copper admixture almost has no influence on the thermal conductivity of such plasma mixture in experimental temperature range 3000 K < T < 6000 K. So, in this approach the thermal conductivity λ of air without any admixtures was used. The electric field *E* of arc plasma column was measured additionally by discharge length varying. It must be noted that in equation (1) radiation losses term is neglected.

Our preliminary estimation of radiation losses, caused by emission of copper spectral lines, showed that influence of this mechanism is insignificant for the temperatures up to 8500 K.

Additionally we can note that just similar conclusion was made in paper [9], where author showed that radiation losses of arc between carbon electrodes is negligible in the current range up to 30 A.

So, radial distribution of electrical conductivity can be calculated in the following manner:

$$\sigma(r) = -\frac{1}{rE^2}\left[\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right)\right]. \qquad (2)$$

In Fig. 1 electrical conductivity radial profiles of electric arc plasma are shown. Additionally this plasma parameter of arc between copper and brass electrodes for comparison is shown. Calculated data (from equation (2)) was approximated by Gaussian curves according to three different temperature profiles T, T_{Sup} and T_{Inf}.

The procedure of approximation was carried out under strong requirements of true value of experimental discharge current.

At the next step of investigation the radial profiles of electron density in arc discharge were obtained from calculated profiles of electrical conductivity.

2.2. ELECTRON DENSITY CALCULATION

Since the mobility of electron is much higher than the ion mobility, the ion current in plasma can be neglected. Then plasma electrical conductivity can be written as:

$$\sigma(r) = eN_e(r)\mu_e(r), \qquad (3)$$

where *e* is the elementary electrical charge, $N_e(r)$ – electron density distribution, μ_e – electron mobility, which can be expressed in terms of the frequency collisions of electron with other particles:

$$\mu_e(r) = \frac{e}{m_e \nu_t(r)}, \qquad (4)$$

where m_e is the mass of electron, ν_t – frequency collisions of electron with particles of all sorts, which can be written as:

$$\nu_t(r) = \sum_p \nu_{e-p}(r), \qquad (5)$$

$$\nu_{e-p}(r) = N_p(r)\cdot\left\langle u_e \cdot Q_{e-p}\right\rangle, \qquad (6)$$

where ν_{e-p} is the frequency collisions of electron with particles of sort "*p*", $N_p(r)$ – the radial distribution of particle density of sort "*p*" and $\langle u_e Q_{e-p}\rangle$ – the average product of electron velocity and collision cross section for particles of sort "*p*". It was assumed that plasma is in LTE, so Maxwell distribution was used in calculation of the average value $\langle u_e Q_{e-p}\rangle$ in equation (6).

Thus, electron densities can be obtained from equations (3)-(6). Peculiarities of performed calculation of plasma composition and the cross sections determination are discussed in detail in paper [8].

In Fig. 2 radial profiles of electron densities in electric arc plasma column are shown. Simulations were carried out on the base of obtained electrical conductivities according to three different temperature profiles T, T_{Sup} and T_{Inf}. In case of electric arcs between copper electrodes in air flow at currents 3.5 and 30 A experimentally measured radial profiles of electron density in plasma between copper electrodes in air flow are additionally shown in Figs. 2,b,c [6].

One can conclude that agreement between experimental and calculated electron density in plasma of arc discharge between copper and brass electrodes is more or less acceptable. Unfortunately, experimental validation of electron densities in electric arc between composite Cu-C is not carried out due to difficulties of measurement techniques adaptation in this arc operation mode. Nevertheless, calculated radial profiles of electron density in electric arc between these electrodes seem to be quite reasonable. At the next step of investigation another kind of experimental techniques must be used to obtain such profiles.

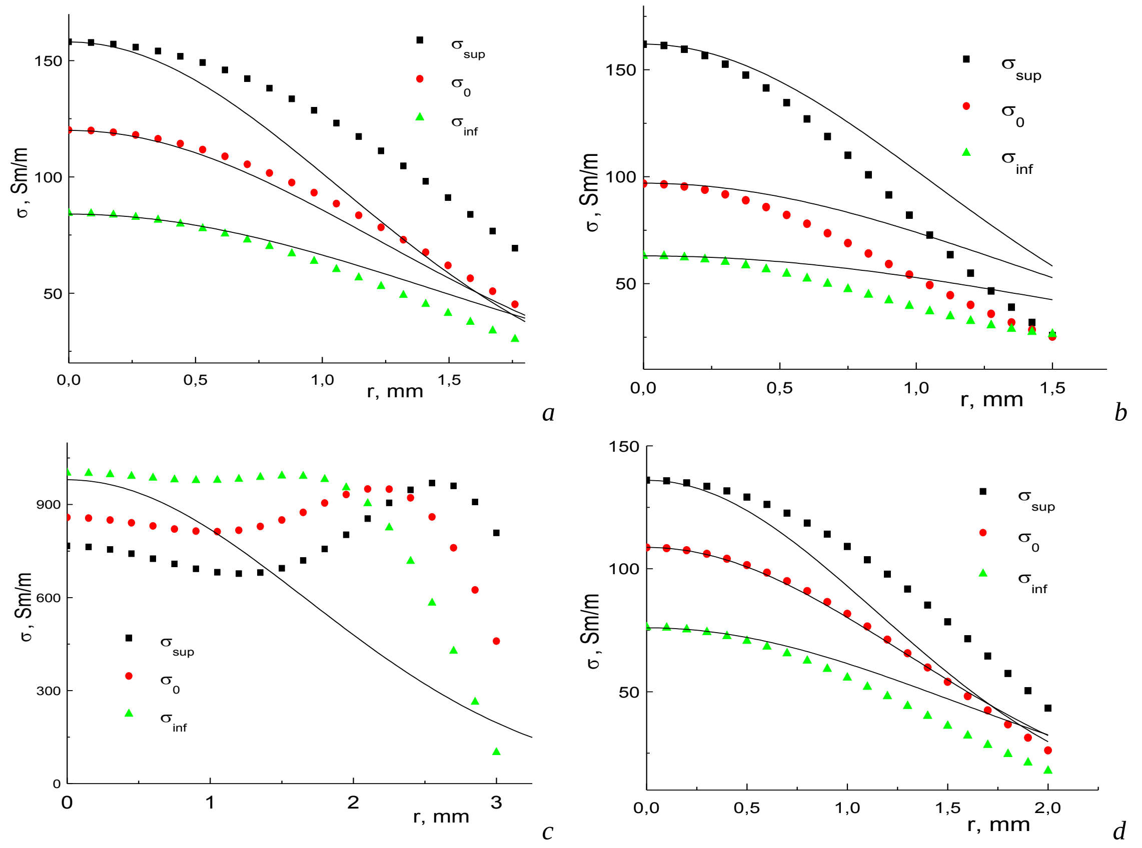

Fig. 1. Radial profiles of electrical conductivity calculated from equation (2) and approximation curves σ_T, σ_{TSup} and σ_{TInf} in discharge gap of electric arcs between Cu-C electrodes at current 3.5 A in air (a) and between copper electrodes in air flow at currents 3.5 A (b) and 30 A (c), and between brass electrodes at current 3.5 A (d)

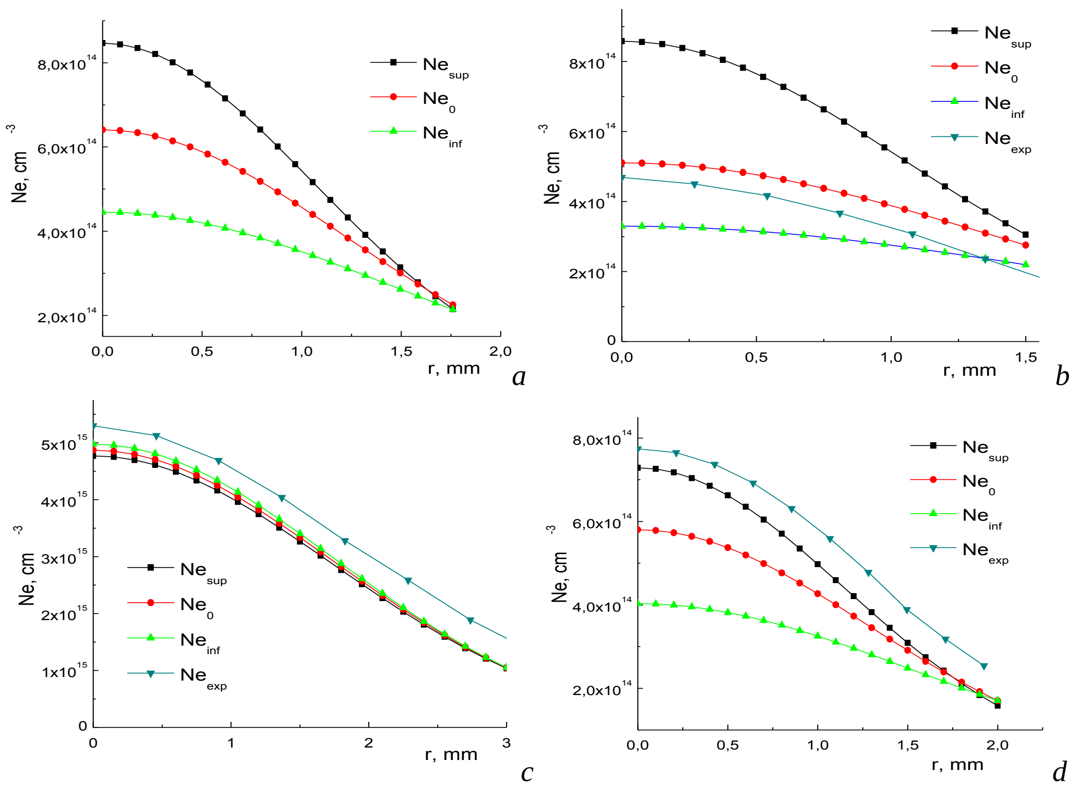

Fig. 2. Radial profiles of electron densities obtained from σ_T, σ_{TSup} and σ_{TInf} in discharge gap of electric arcs between Cu-C electrodes in air at current 3.5 A (a) and copper electrodes in air flow at currents 3.5 A (b) and 30 A (c), and between brass electrodes in air at current 3.5 A (d). Experimentally measured profiles are shown as Ne_{exp}

CONCLUSIONS

The complex technique of plasma property studies is suggested. From one hand, the radial profiles of temperature and electron density in plasma of electric arc discharge in air between Cu-C composite and brass electrodes, as well as copper electrodes in air flow were measured by optical spectroscopy techniques. From another hand, the radial profiles of plasma electric conductivity were calculated by solution of energy balance equation. The electron density was obtained from the electric conductivity profiles by calculation in LTE assumption and taking into account that thermal conductivity is not affected by electrode material admixtures.

The good agreement between experimental and calculated in such way electron densities in plasma of electric arc discharge between copper electrodes in air flow is found. So such approach can be recommended for low temperature thermal plasma diagnostics.

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ТЕРМИЧЕСКАЯ ПЛАЗМА ЭЛЕКТРОДУГОВОГО РАЗРЯДА В ВОЗДУХЕ МЕЖДУ КОМПОЗИТНЫМИ Cu-C-ЭЛЕКТРОДАМИ

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Предложена комплексная методика исследования плазмы. На первом этапе методами оптической эмиссионной спектроскопии проводились измерения радиальных распределений температуры и электронной концентрации в плазме электродугового разряда в воздухе между композитными Cu-C и латунными электродами, а также медными электродами в потоке воздуха. На следующем этапе рассчитывались радиальные распределения электропроводности плазменной смеси путем решения уравнения энергетического баланса. Распределение электронной концентрации получено из электропроводности плазмы в допущении локального термодинамического равновесия.

ТЕРМІЧНА ПЛАЗМА ЕЛЕКТРОДУГОВОГО РОЗРЯДУ В ПОВІТРІ МІЖ КОМПОЗИТНИМИ Cu-C-ЕЛЕКТРОДАМИ

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Запропонована комплексна методика дослідження плазми. На першому етапі методами оптичної емісійної спектроскопії проводились дослідження радіальних розподілів температури та електронної концентрації в плазмі електродугового розряду в повітрі між композитними Cu-C та латунними електродами, а також мідними електродами в потоці повітря. Наступним кроком розраховувались радіальні розподіли електропровідності плазмової суміші шляхом розв’язку рівняння енергетичного балансу. Розподіл електронної концентрації отримали з електропровідності плазми в припущенні локальної термодинамічної рівноваги.