doi:10.14311/ppt.2019.1.27
Plasma Physics and Technology **6**(1):27–30, 2019

THERMAL PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN Cu–Cr COMPOSITE ELECTRODES

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Abstract. This work deals with investigations of model plasma source realised as electric arc discharge in gas atmosphere between Cu–Cr composite electrodes. Radial distributions of temperature and electron density in arc plasma column were studied by optical emission spectroscopy. The content of electrode metals' vapours in discharge was calculated on the base of experimentally obtained plasma parameters as initial data. So, in this way the erosion properties of such composition can be determined.

Keywords: optical emission spectroscopy, plasma of arc discharge, erosion of surface electrode, composite materials, electrical contact.

1. Introduction

Composite materials on copper base with addition of refractory metals, particularly chromium, have advanced applications in electric power industry. Namely, such composition are mostly used as contact material in vacuum arc-quenching chambers of high and middle loads systems [1, 2]. The erosion properties of abovementioned material play key role, which determined the efficiency of circuits' commutation performance.

It is well-known that heterogeneous compound materials of two or more components with different melting and boiling points, such as Cu–Cr, are mostly manufactured by sintering and/or infiltration techniques. The compositions between 75/25% and 50/50% by weight of Cu–Cr contact material has proved optimum behavior in many respects for circuit-breakers [1–3]. Namely, high breaking capacity, gettering effect, smooth surface after arcing with subsequent high electrical strength, moderate chopping current of such composition are just those properties which are required in this kind apparats [1].

There are some investigations of plasma produced by high current vacuum arcs between Cu–Cr contacts in literature. Namely, in paper [3] was shown, that microparticles can be produced during interruption of a high current vacuum arc between such contacts. It is the reason, which causes the reduce of the insulation performance of vacuum interrupters. The authors concluded, that the contact material has a great effect on the particle generation patterns. It was found that it is much more difficult to form a melting pool on a Cu–Cr contact surface with a higher proportion of chromium. The refractory material can suppress the flow of metal liquid and, consequently, fewer particles can be produced from it.

In paper [4] the spatially resolved optical emission spectroscopy was used to study plasma parameters of high-current vacuum arcs between Cu–Cr contacts. It was found that the plasma layer in front of the anode is not in local thermal equilibrium (LTE). The two-temperature plasma model is suggested by authors to use in study of such non-equilibrium plasma areas.

The aim of this paper is investigation of plasma parameters of model source realised as electric arc discharge in air atmosphere between Cu–Cr composite electrodes. In assumptions of LTE the optical emission spectroscopy techniques are developed to study the content of electrode metals' vapours in discharge, which can be calculated on the base of experimentally obtained plasma parameters as initial data.

The results of calculation of metal component concentration in arc discharge plasma can be used and applied to development and optimization of novel composite materials.

2. Experimental setup

2.1. Measurements of temperature

The arc was ignited between the end surfaces of vertically-oriented non-cooled copper-chromium electrodes. Electrodes were produced by powder metallurgy in the form of a rectangular parallelepiped with a cross section 3.5×3.5 mm. The Cu–Cr composite was formed at a temperature of $750°C$ in a volume ratio of 65% Cr and 35% Cu. Discharge gap was of 8 mm and arc current 3.5 A.

Radial profiles of emission intensities in the average cross section of the free burning in air electric arc plasma were investigated. Technique of one-pass tomographic recording of the spatial distribution of spectral line intensities was used [5]. Monochromator MDR-12 with 3000-pixels CCD linear image sensor Sony ILX526A (B/W) accomplished fast scanning of spatial distribution of radial intensity. Due to the instability of the discharge, statistical averaging of the recorded spatial distributions of the radiation characteristics was carried out.

Because side-on (lateral) observation of plasma object was realized in proposed experimental setup, it is necessary to use Abel inversion [6] for obtaining of local values of intensity.

The radial distributions of plasma temperature were determined in the middle section of discharge gap. The techniques of Boltzmann plot in the assumption of local thermodynamic equilibrium (LTE) were used. In this study spectral lines Cu I 510.5 nm, 515.3 nm, 521.8 nm, 570 nm, 578.2 nm, 793.3 nm, 809.3 nm and Cr I 435.1 nm, 458 nm, 464.6 nm, 487 nm, 532.8 nm, 540.9 nm were used.

It must be noted, that in our previous investigation [7] of electric arc discharge between Cu–Cr electrodes with addition of 1% of W the realisation of LTE in plasma column was found at the same arc current. It is a reason of the application of such model in the frame of this study.

2.2. Electron density measurements

The electron density was obtained from electric conductivity, which can be calculated by solution of energy balance equation (Elenbaas-Heller) in assumption of LTE in plasma. Preliminary, the measurement of electric field has been carried out in positive plasma column of arc discharge. So, radial distribution of electrical conductivity can be calculated in the following manner:

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

It must be noted, that radiation loss term was neglected in Eq.1 according to results of work [8]. The author found, that the arc radiation losses are insignificant for current up to 30 A.

It must be noted as well, that according to results, obtained in [9], the metal vapour does not noticeably change the thermal conductivity of air as plasma-forming gas in the investigated temperature range. Naturally, we took into account the temperature dependency of air thermal conductivity.

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

$$\sigma(r) = eN_e(r)\mu_e(r), \qquad (2)$$

where e is the elementary electrical charge, $N_e(r)$ - electron density distribution, μ_e - electron mobility.

Thus, electron densities can be obtained from Eq.1-2. Peculiarities of performed calculation of electron density in plasma and the cross sections determination are discussed in detail in papers [10, 11].

2.3. Calculation of plasma composition

The calculation of the component composition of the plasma in the air atmosphere with the impurities of copper and chromium vapours is performed on the base of the preliminary determined radial distributions of the temperature $T(r)$ and the electron density $N_e(r)$ (Fig.1). In addition, the radial profiles of two spectral lines intensities of different elements were used. Namely, copper and chromium atoms spectral lines intensities were measured to obtain the necessary in calculation the ratio of these element concentrations.

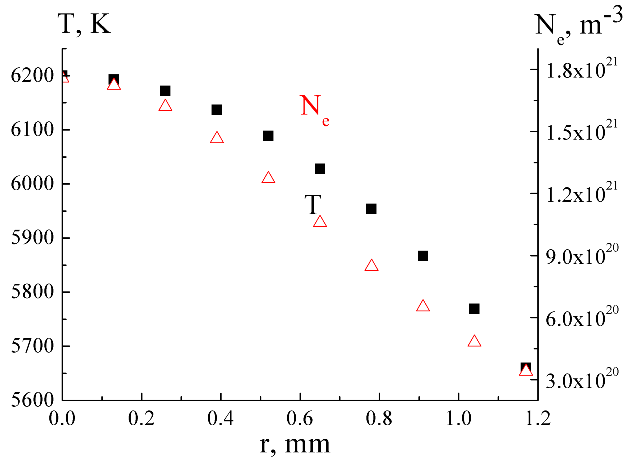

Figure 1. Radial distributions of plasma temperature and electron density of arc discharge between composite Cu–Cr electrodes at current 3.5 A.

To calculate the component composition on the base of the aforementioned parameters, the following set of equations is solved:

1. four Saha equations for atoms of copper, chromium, nitrogen and oxygen:

$$S_i(T, N_e) = \frac{N_e N_i^+}{N_i}, \quad i \to \mathrm{Cu, Cr, N, O}; \qquad (3)$$

2. two equations for dissociation of nitrogen and oxygen molecules:

$$D(T) = \frac{N_i^2}{N_{i2}}, \quad i \to \mathrm{N, O}; \qquad (4)$$

3. electroneutrality equation:

$$N_e = \sum N_i^+, \quad i \to \mathrm{Cu, Cr, N, O}; \qquad (5)$$

4. perfect gas equation:

$$B(T) = N_e + N_{\mathrm{O_2}} + N_{\mathrm{N_2}} + \sum N_i + \sum N_i^+ \quad i \to \mathrm{Cu, Cr, N, O}; \qquad (6)$$

5. the ratio between the number of nitrogen and oxygen particles in the air:

$$(N_{\mathrm{N}} + 2N_{\mathrm{N}_2} + N_{\mathrm{N}^+}) = \\ = 3.72(N_{\mathrm{O}} + 2N_{\mathrm{O}_2} + N_{\mathrm{O}^+}). \quad (7)$$

To solve this set of equations, it was necessary to define additionally the radial profile of the ratio between the concentrations of different metals atoms N_{Cu} and N_{Cr}. With this aim, the intensities of spectral lines Cu I 515.3 nm and Cr I 540.9 nm in the plasma radiation were experimentally measured in the assumption of Boltzmann population distribution of copper and chromium atom levels (see Fig.2).

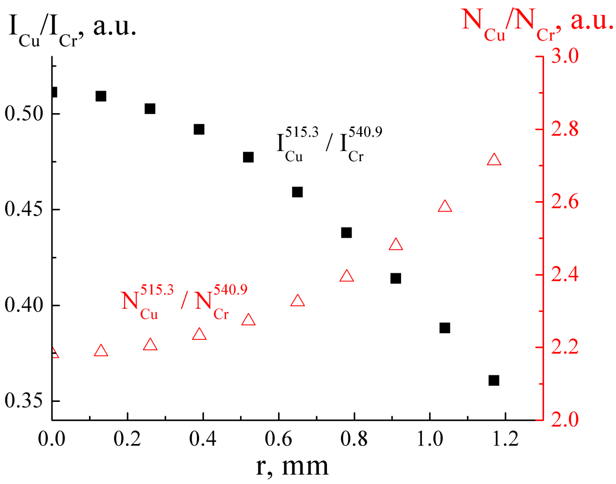

Figure 2. The ratio of the radiation intensity of the spectral lines Cu I 515.3 nm and Cr I 540.9 nm (■). The ratio of concentrations of copper and chromium atoms (△).

3. Results and Discussions

Calculated plasma composition in assumption of LTE was used to obtain the radial profiles of copper X_{Cu} and chromium X_{Cr} vapour contents in mid-section of arc discharge channel. These contents are defined as follows:

$$X_{\mathrm{Cu}}, \% = (N_{\mathrm{Cu}} + N_{\mathrm{Cu}^+}) \cdot 100 / \sum_j N_j, \quad (8)$$

$$X_{\mathrm{Cr}}, \% = (N_{\mathrm{Cr}} + N_{\mathrm{Cr}^+}) \cdot 100 / \sum_j N_j. \quad (9)$$

The total concentration of particles in plasma $\sum_j N_j$ without electron density is used in Eq.8-9.

In Fig.3 the radial distributions of copper and chromium vapours contents in plasma of electric arc discharge in air between composite Cu–Cr electrodes at current 3.5 A are shown. It must be noted, that in spite the fact, that chromium in the electrode material plays role as refractory component, the content of both metals in plasma is comparable. Moreover, it must be stressed, that electrical conductivity in plasma of arc discharge channel was provided just mainly by thermal ionization of chromium component (see Fig.4). This phenomenon can be explained due to the relatively low ionization energy of chromium atom (6.76 eV) in comparison with copper atom (7.74 eV).

The qualitatively and quantitatively behavior of metal vapours contents in mid-section of arc discharge channel does not reflect in fact the real distribution of metal concentration near electrodes working surface. Nevertheless, the suggested in this study techniques can be used as indirect way with aim of study of composition material erosion properties.

To clarify the role of air atmosphere in such erosion behavior of both metal component in electrode composition it seems reasonable to carry out similar study of plasma parameters of arc discharge in argon flow at the next stage of investigation.

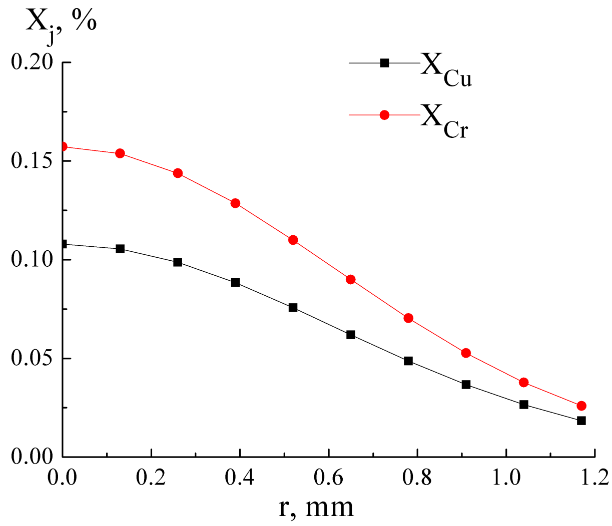

Figure 3. The radial distributions of copper and chromium vapours contents in plasma of electric arc discharge between composite Cu–Cr electrodes at current 3.5 A.

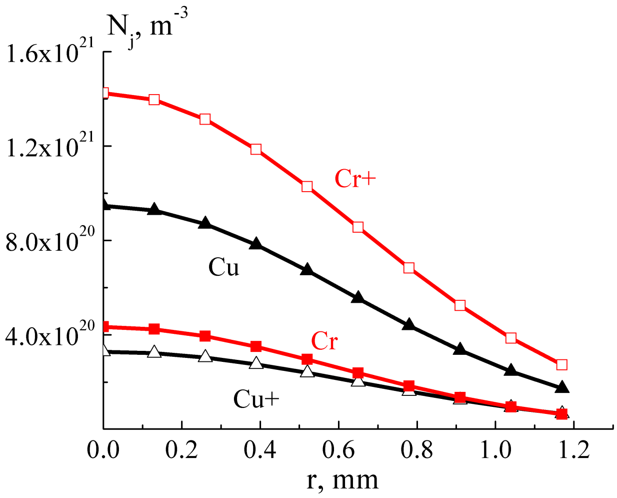

Figure 4. The radial distributions of Cu, Cr atoms and Cu^+, Cr^+ ions concentrations.

4. Conclusions

Plasma parameters of electric arc discharge in air atmosphere between Cu–Cr composite electrodes were investigated. In assumptions of LTE the optical emission spectroscopy techniques are developed to study erosion properties of such composite materials.

It was found, that in spite of the fact, that chromium in the electrode material plays role as refractory component, the content of both metals in plasma is comparable. The electrical conductivity in plasma of arc discharge channel was provided just mainly by thermal ionization of chromium component. This phenomenon can be explained due to the relatively low ionization energy of chromium atom in comparison with copper atom.

Acknowledgements

This work was supported by joined project in the frame of research and technology collaboration between Ukraine and Czech Republic No.7AMB197UA.

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