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SPECTROSCOPY OF PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN Cu-Mo COMPOSITE ELECTRODES

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Abstract. This work is devoted to the study of thermal plasma of electric arc discharges between composite Cu-Mo electrodes by optical diagnostic techniques. The electrodes were fabricated from copper–molybdenum composite materials. The arc discharge was ignited in an argon flow at a direct current of 3.5 A and a discharge gap of 8 mm. The absolute intensities of the spectral lines emitted by the plasma were registered in the spectral range of 430–650 nm. Radial distributions of key plasma parameters, namely excitation temperature and number densities of metals, were determined. For this purpose, the Boltzmann plot technique was applied using selected spectral lines of Cu I and Mo I. Particular attention was paid to the applicability of the local thermodynamic equilibrium assumption in the arc plasma under such discharge conditions.

Keywords: Thermal plasma, optical emission spectroscopy, composite electrodes, copper, molybdenum.

1. Introduction

Mo-Cu composite materials still remain in the focus of attention of the industry for the development of novel materials. These composites are used as materials for contacts of switching devices in systems of various loading degrees [1], in particular: vacuum arc extinguishing chambers and low-voltage sliding contacts for mine non-high-speed railways [2, 3]. Cu-Mo composite materials are used in cooling elements and heat dissipation in components of electronic devices, such as microwave integrated circuits, insulated gate bipolar transistors, diode lasers or light-emitting diodes [4].

A wide range of their applications requires diversifying and improving the manufacturing technologies of such composites. In particular, novadays there are known technologies for manufacturing molybdenum-copper materials by powder metallurgy, electron beam evaporation with subsequent condensation in a vacuum, [5, 6] etc. In the work [7] an original method of densification and improvement of the properties of powder Mo-Cu composites is proposed. In the work [8], optical emission spectroscopy (OES) methods were used to compare the erosion properties of Mo-Cu composites obtained by two different powder metallurgy and vacuum condensation technologies.

In this paper the erosion properties of Mo-Cu composites with different content of molybdenum and copper, obtained by powder metallurgy technology, were studied by OES as a result of the interaction of arc discharge plasma with an electrodes surface.

2. Experimental setup

The plasma of DC electric arc discharges between different type of electrodes made of Mo-Cu composite material are investigated by OES. To eliminate the influence of oxygen in open atmosphere, experiments were carried out in an argon flow. Three types of composite materials were investigated: Mo-25Cu, Mo-75Cu, and Mo-50Cu (in wt.%). The last one composite type contained a small impurity of Al_2O_3 (does not exceed 2%). These composites were fabricated by the shock sintering technology at a temperature of 1000°C.

Rectangular electrodes with a square cross-section of 4×4 mm were used. The discharge gap was maintained at 8 mm. The discharge current at 3.5 Amps was used. Optical emission spectra were registered with spatial resolution in the midsection of arc discharge (4 mm from electrode surface) using a calibrated spectroscopic system. The absolute emission intensities of selected Cu I and Mo I lines were measured. The following spectral lines were identified in the emission spectrum (see Figure 1) and used to determine radial distributions of plasma temperature and number densities of copper and molybdenum atoms by Boltzmann plot technique: Mo I 457.6, 461.0, 466.3, 467.2, 470.7, 473.1, 476.0, 481.9, 483.1, 486.8, 495.1, 495.8, 497.9, 536.1, 563.2, 565.0, 568.9, 572.3, 575.1, 579.2, 585.8, 588.8 nm and Cu I 510.5, 515.3, 521.8, 570.0, 578.2 nm. The inverse Abel transform by Bockasten method at 10 points was used to obtain radial distributions of spectral line emission intensity from the side-on spectra, assuming that the arc has axial symmetry [9]. Figure 2 shows the spatial distributions

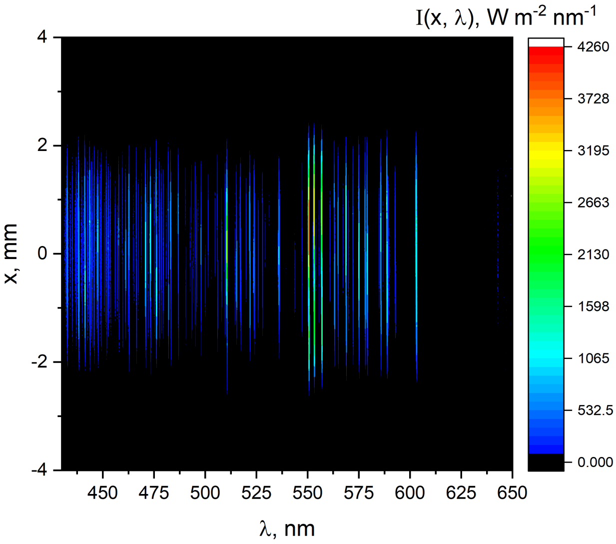

Figure 1. Typical spatially resolved emission spectrum of the plasma of arc discharge between Mo-25Cu composite electrodes

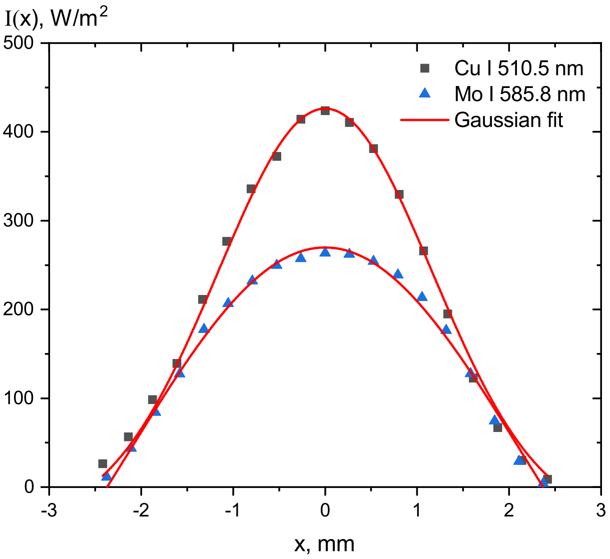

Figure 2. Typical spatial distribution of Cu I 510.5 nm (squares) and Mo I 585.8 nm (triangles) spectral lines observed in the midsection of arc discharge between Mo-25Cu composite electrodes

of the observed radiance ($I(x)$) of the Cu I 510.5 nm (squares) and Mo I 585.8 nm (triangles) spectral lines, as well as their fitting by a Gaussian (curve). One can see that the experimentally obtained data are in good agreement with the fitting curves centered at the point $x = 0$ mm. Since the Gaussian is a symmetric function, such a coincidence confirms our assumption about the axial symmetry of the arc discharge. The spectroscopic data for aforementioned spectral lines was taken from [10–12]. A more detailed description of the setup and the experimental data processing can be found in previous works [13].

Typical Boltzmann plots based on the absolute emission intensity of Cu I (squares) and Mo I (circles)

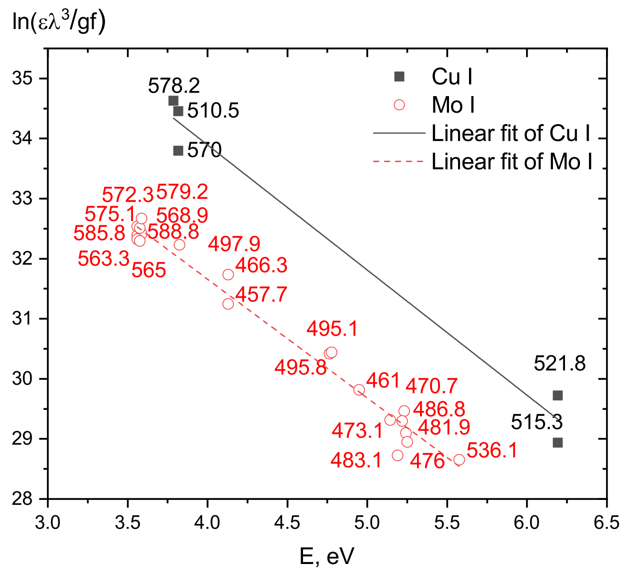

Figure 3. Typical Boltzmann plots based on the absolute emission intensity of Cu I (squares) and Mo I (circles) spectral lines constructed at axial radial point ($r = 0$ mm) of arc discharge between Mo-50Cu composite electrodes

spectral lines constructed at axial radial point ($r = 0$ mm) of arc discharge between Mo-50Cu composite electrodes are shown in Figure 3. One can see that the dots on the Boltzmann plots are in good agreement with the linear fits, which indicates a low measurement error (does not exceed 5%).

The erosion properties of Mo-Cu composites can be estimated by indirect way from the radial distributions of metal vapor contents in plasma, which can be calculated as follows [8]:

$$X_j(r) = \frac{n_j(r) + n_j^+(r)}{\Sigma n_i(r)} \qquad (1)$$

where j is corresponded to copper or molybdenum, $n_j(r)$ is radial distribution of number density of copper or molybdenum atoms, $n_j^+(r)$ is radial distribution of number density of copper or molybdenum ions, $n_i(r)$ is radial distribution of number density of i^{th} component in plasma ($i \to$ Ar, Ar^+, Cu, Cu^+, Mo, Mo^+). Unknown number densities of other plasma components can be calculated from the equilibrium plasma composition in the assumption of local thermodynamic equilibrium (LTE) by solving a system of equations with radial distributions of plasma temperature and number densities of copper and molybdenum atoms as input parameters [12].

It is worth noting that the results of this work were obtained from a single spectrum for each case. For a more in-depth analysis, it is necessary to carry out statistical processing on several spectra. However, it can be expected that the variability of the plasma parameters still will be within the measurement error.

3. Results and Discussions

The radial distributions of plasma temperature obtained by Boltzmann plot technique based on the emission intensities of both Cu I and Mo I spectral lines in the plasma of arc discharge between each type of electrodes are shown in Figure 4. One can see that the temperatures determined based on the copper (T_{Cu}) and molybdenum (T_{Mo}) spectral lines coincide within the error bars along the entire spatial range under study. From this one can conclude that the equilibrium population of the energy levels of atoms is realized according to the Boltzmann distribution in the plasma of electric arc discharges between each type of electrodes. In turn, this allows one to make an assumption about the realization of LTE in such plasma, which makes it possible to calculate the equilibrium plasma composition.

Since the equilibrium composition model requires only one temperature profile as an input parameter, a validation procedure was performed for the Mo-75Cu electrode configuration. In the first case, the radial distribution of temperature obtained based on emission intensity of Cu I spectral lines was used as input data. The number density of molybdenum atom was determined using the Boltzmann distribution based on this temperature and the population of the upper energy level of Mo I 585.8 nm spectral line. In the second case, the temperature profile obtained based on Mo I spectral lines was used, and the number density of copper atom was calculated from the upper level population of the Cu I 510.5 nm line. As was noted before, in the both approaches, the populations were obtained from the absolute intensities of the corresponding spectral lines. The radial distributions determined via Boltzmann plots (n_{Cu} and n_{Mo}) technique and those calculated from level populations (n_{Cu} from T_{Mo} and n_{Mo} from T_{Cu}) are presented in Figure 5.

One can see that the number densities profiles obtained directly from the Boltzmann plots and from the recalculation from the population of a specific energy level almost completely coincide. This makes it possible to use any studied temperature profile to calculate the equilibrium plasma composition. The radial distributions of plasma temperature and number density of copper atoms obtained by Boltzmann plot technique based on the emission intensity of the Cu I spectral lines were used as input parameters for further calculations of the equilibrium plasma composition. The last input parameter was the radial distribution of number density of molybdenum atoms obtained from the population of the upper energy level of the Mo I 585.8 nm spectral line.

The obtained equilibrium compositions of the plasma of arc discharges between composite Mo-25Cu, Mo-75Cu, and Mo-50Cu electrodes are shown in Figures 6, 7 and 8, respectively. It is worth noting that for the case of Mo-50Cu electrodes, the number densities of aluminum and oxygen were considered negligibly small when calculating the composition, since the emission of these elements was not observed in the spectrum at all.

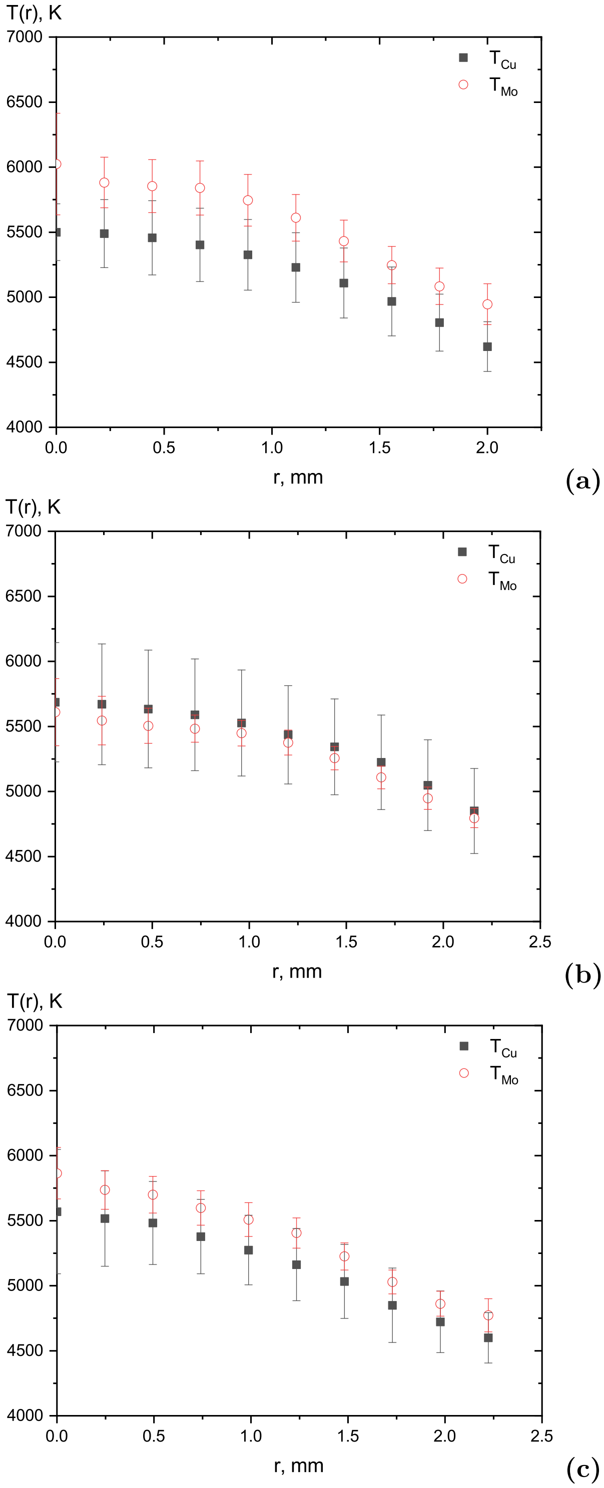

Figure 4. Radial distributions of plasma temperature obtained by Boltzmann plot technique based on the emission intensities of both Cu I (squares) and Mo I (circles) spectral lines in plasma of arc discharge between (a) Mo-25Cu, (b) Mo-75Cu, and (c) Mo-50Cu composite electrodes.

One can see from Figures 6-8 that the number density of copper atoms in the discharge plasma between

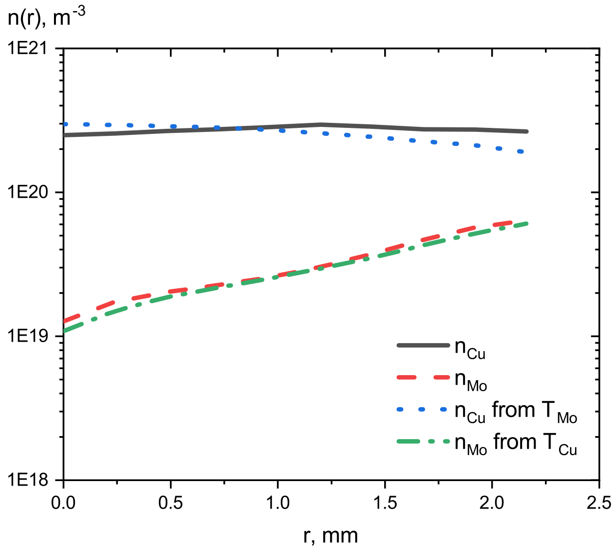

Figure 5. Radial distribution of number densities of copper and molybdenum atoms obtained by directly Boltzmann plot technique and calculated based on different temperature distribution in the plasma of arc discharge between Mo-75Cu composite electrodes.

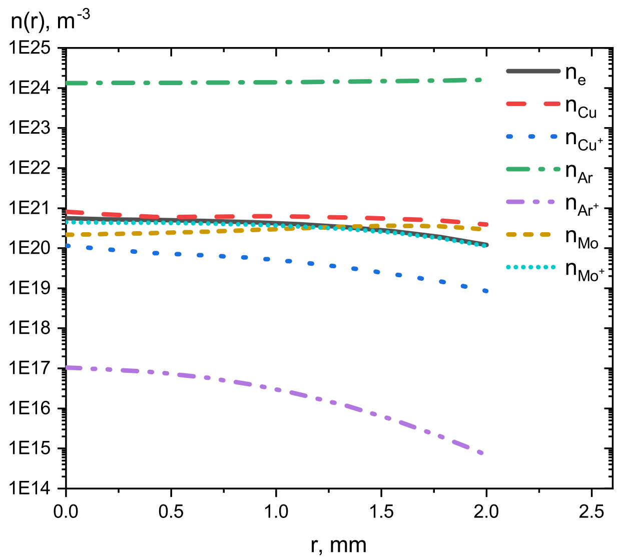

Figure 6. Equilibrium composition of plasma of arc discharge between Mo-25Cu composite electrodes.

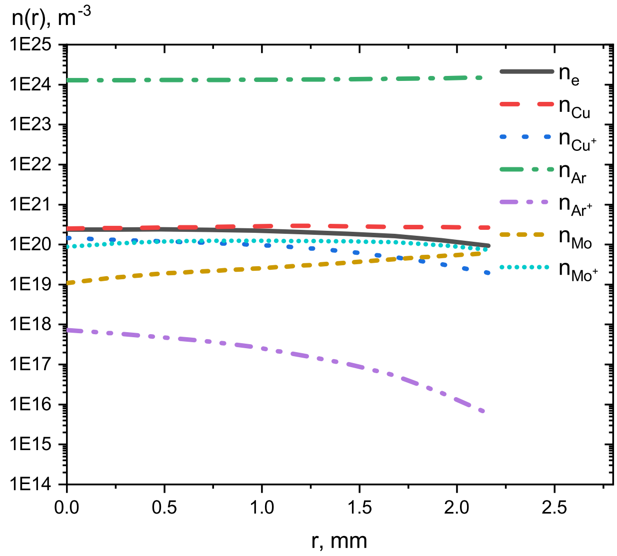

Figure 7. Equilibrium composition of plasma of arc discharge between Mo-75Cu composite electrodes.

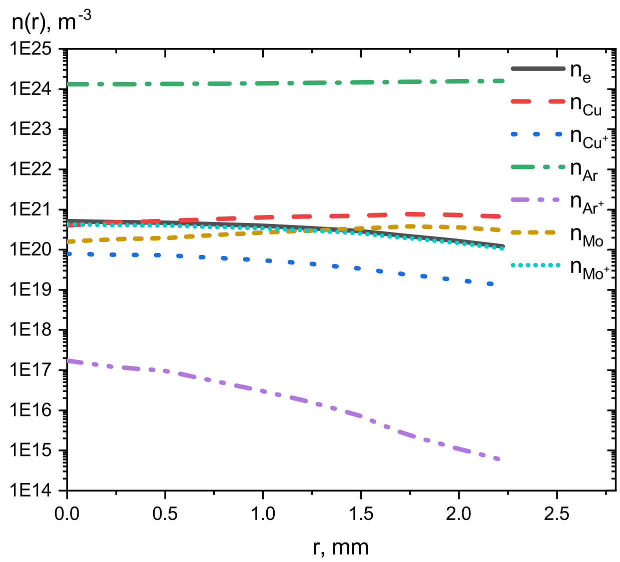

Figure 8. Equilibrium composition of plasma of arc discharge between Mo-50Cu composite electrodes.

all types of electrodes is higher than that of molybdenum atoms. In turn, the plasma conductivity in the case of a discharge between electrodes with a 75% copper content is determined by the ionization of copper and molybdenum almost equally. As for the other two cases, approximately 90% of the electrons are caused by the thermal ionization of the molybdenum component. This is obviously explained by the comparatively high molybdenum content in the electrodes (50% and 75%), as well as its low ionization potential (7.092 eV compared to 7.727 eV for copper).

The radial distributions of metal vapors content (X_{Cu} and X_{Mo}) in the plasma of arc discharge between Mo-25Cu, Mo-75Cu, and Mo-50Cu composite electrodes are shown in the Figures 9, 10 and 11, respectively. It is evident that the amount of copper vapor is almost equal to the amount of molybdenum vapor in the cases of arc discharge between Mo-25Cu and Mo-50Cu electrodes. For the case of Mo-75Cu, the amount of copper vapor exceeds the molybdenum vapor content. In addition, an off-axis maxima of the metal vapor content can be observed in Figures 10 and 11. Under conditions of constant pressure and plasma temperature gradient, an increase in the ionization efficiency of metal atoms on the arc discharge axis (see Figures 6-8) can lead to the off-axis maximum of the number density of these metal atoms, which, obviously, causes the off-axis maxima of the metal vapor content.

Moreover, it is clearly seen that in the arc discharge plasma between the composite electrodes with 25%

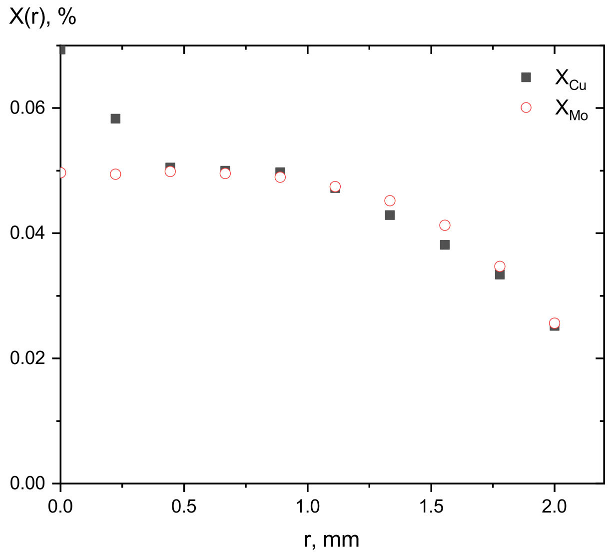

Figure 9. Radial distributions of metal vapor content in the plasma of arc discharge between Mo-25Cu composite electrodes.

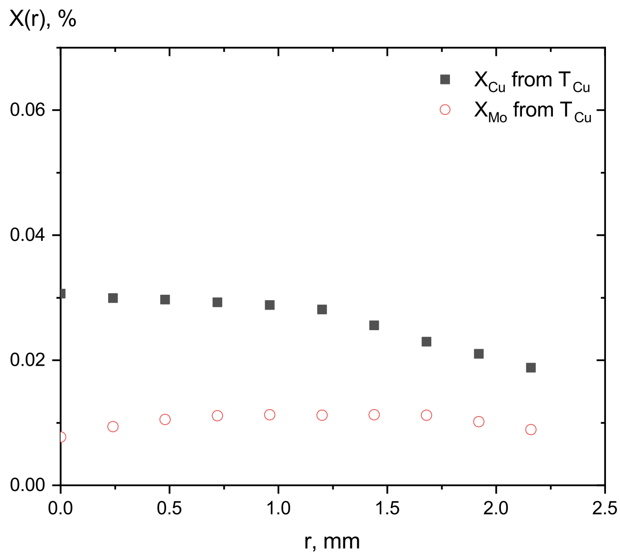

Figure 10. Radial distributions of metal vapor content in the plasma of arc discharge between Mo-75Cu composite electrodes.

molybdenum part, the total amount of metal vapors ($X_{Cu} + X_{Mo}$) is the smallest (see Figure 12). This indicates that this type of composites is most resistance to arc erosion compared to other types of composites studied in this work. Despite the higher melting point of molybdenum compared to copper (2896 K and 1358 K, respectively), an increase in its part in the composite material leads to deterioration of erosion resistance. The reason for the increase in the amount of metal vapors in the plasma with an increase in the molybdenum content in the composite is probably associated with a significant deterioration in thermal conductivity (139 W/mK for molybdenum and 400 W/mK for copper).

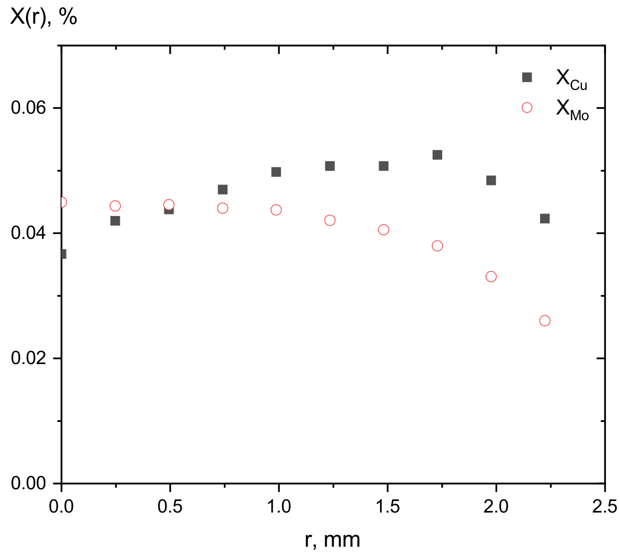

Figure 11. Radial distributions of metal vapor content in the plasma of arc discharge between Mo-50Cu composite electrodes.

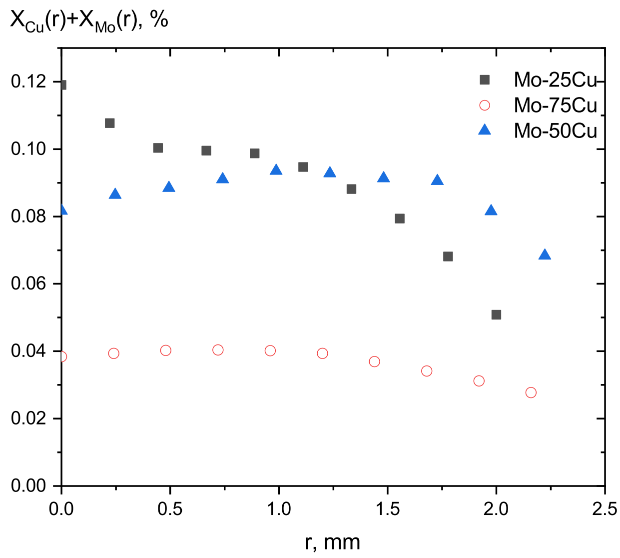

Figure 12. Radial distributions of total metal vapor content in the plasma of arc discharge between each type of composite electrodes.

4. Conclusions

In this study, the plasma of DC arc discharges between Mo-Cu composite electrodes was investigated using spatially resolved optical emission spectroscopy. Three electrode compositions, namely Mo-25Cu, Mo-75Cu, and Mo-50Cu, were tested under identical discharge conditions. Radial distributions of plasma temperature and number densities of metal atoms were obtained using the Boltzmann plot technique based on the absolute emission intensities of both Cu I and Mo I spectral lines.

The temperatures determined independently based on Cu I and Mo I spectral lines were found to be in good agreement within the experimental error, confirming the assumption of realization of local thermodynamic equilibrium in the plasma. This validation enabled the calculation of the equilibrium plasma composition and, in turn, metal vapor content in the plasma.

A detailed comparison of number densities derived directly from Boltzmann plots and those recalculated from population levels confirmed the consistency of the diagnostic methods used. The results showed that in the Mo-75Cu discharge, ionization of both copper and molybdenum significantly contributed to plasma conductivity, whereas in the other two cases, molybdenum ionization played the dominant role.

Analysis of metal vapor content in the discharge plasma revealed that the total vapor content was lowest in the Mo-75Cu composition configuration, indicating better resistance to the arc erosion. Despite molybdenum's higher melting point, its lower thermal conductivity compared to copper may lead to increased vaporization under arc conditions. These findings demonstrate that increasing molybdenum content in Mo-Cu composites can reduce their erosion resistance, highlighting the importance of optimizing material composition for arc applications.

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