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PLASMA PROPERTIES OF ELECTRIC ARC DISCHARGE BURNING BETWEEN CU-W COMPOSITES ELECTRODES

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Abstract. Plasma of electric arc discharge burning between different types of composite Cu-W electrodes was investigated. Electrodes manufactured of Cu-W composite materials (30/70% by mass) by shock sintering technology at temperatures of 750, 850, 950, and 1050°C were used. Optical emission spectroscopy techniques were applied to determine the main plasma parameters. Specifically, the side-on spectra of plasma emission were registered using a space-resolved spectrograph with a CMOS camera as a sensor device. The plasma thermodynamics properties were calculated based on the equilibrium plasma composition, which was determined using experimentally obtained radial distributions of temperatures and atom concentrations of the metals.

Keywords: Plasma propertires, arc discharge, optical emission spectroscopy, composite materials, erosion resistance.

1. Introduction

In recent years, Cu-W composite materials have gained attention due to their enhanced mechanical and thermal properties compared to conventional electrode materials. These composite materials combine the desirable properties of high electrical conductivity, refractoriness, and high erosion resistance, thanks to the absence of chemical interaction between metals in both the solid and liquid phases. These unique features, coupled with their superior mechanical properties [1], have led to increased demand for copper-tungsten composites in various applications, including as contact materials [2], heat sink materials [3], and electrical discharge machining electrodes [4], among others.

Understanding the behaviour of plasma in arc discharges and its interaction with composite electrodes is essential for optimizing the performance and lifespan of these systems [5]. The plasma parameters, including temperature, composition, and thermodynamic properties, have a significant influence on the erosion resistance of the electrodes and the efficiency of energy dissipation in the discharge. Accurate characterization and analysis of these plasma parameters are therefore crucial for improving the overall performance of Cu-W composite electrodes.

The main aim of this work is to investigate the plasma of electric arc discharges burning between different types of Cu-W composite electrodes and to complete the study of impact of sintering temperature on the erosion resistance to thermal plasma of such composite materials [5].

2. Experiments and calculations

The composite Cu-W materials (30/70% by mass) manufactured at Frantsevich Institute for Problems of Materials Science NAS of Ukraine by shock sintering technology were used. The manufacture of electrodes from the Cu-W composition requires their sintering in hydrogen at sufficiently high temperatures (≥1200°C) with exposure for ≥2 h. At the same time, the shock sintering method makes it possible to obtain high-density parts at much lower temperatures and short exposure times [6]. It has been considered four different types of materials, namely the materials fabricated at shock pressure of 1200 MPa at sintering temperatures of 750, 850, 950, and 1050°C. The electrodes made of such materials have a square cross-section with 5×5 mm. The arc discharges between Cu-W electrodes of different types were initiated in air atmosphere. Discharge gap in each experiments was 8 mm. The current was set to 3.5 A, and the arc voltage drop was measured using a UNI-T UT181A multimeter.

The emission of thermal discharge plasma between each type of Cu-W composite was analyzed using spectroscopic diagnostics. The experimental setup on the basis of a spectrograph with a 600 $\frac{1}{\mathrm{mm}}$ diffraction grating was applied. By analyzing the emission spectra, key plasma parameters, such as excitation temperatures and concentrations of metals, were determined using Boltzmann plots technique based on the absolute emission intensities of copper and tungsten atomic spectral lines, obtained in previous work [5]. These parameters were then utilized to calculate the equilibrium plasma composition and the respective copper and tungsten vapour contents [7]. Furthermore, thermodynamic properties of the plasma, including molar mass M, specific enthalpy h, specific entropy s, and specific heat capacity at constant pressure c_p, were derived from the obtained plasma parameters.

Assuming ideal behaviour the thermodynamic properties of the gaseous system can be calculated from the following system of equations:

The mass density ρ of the system $\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$:

$$\rho = \sum_{i=1}^{N} n_i M_i \tag{1}$$

where n_i is the molar concentration $\left[\frac{\mathrm{mol}}{\mathrm{m}^3}\right]$ and M_i is the molar mass $\left[\frac{\mathrm{kg}}{\mathrm{mol}}\right]$ of a substance.

Molar concentration n $\left[\frac{\mathrm{mol}}{\mathrm{m}^3}\right]$ of the system:

$$n = \sum_{i=1}^{N} n_i \tag{2}$$

Molar mass M $\left[\frac{\mathrm{kg}}{\mathrm{mol}}\right]$ of the system:

$$M(p,T) = \frac{\rho}{n} \tag{3}$$

Specific enthalpy h $\left[\frac{\mathrm{J}}{\mathrm{kg}}\right]$:

$$h(p,T) = \frac{1}{\rho} \sum_{i=1}^{N} n_i \left(\Delta_f H^{\circ}_{i,T_{\mathrm{ref}}} + \Delta H^{\circ}_{i,T_{\mathrm{ref}}}(T)\right) \tag{4}$$

where $\Delta_f H^{\circ}_{i,T_{\mathrm{ref}}}$ is the standard molar enthalpy of formation of the component and $\Delta H^{\circ}_{i,T_{\mathrm{ref}}}(T)$ is the standard molar enthalpy change:

$$\Delta H^{\circ}_{i,T_{\mathrm{ref}}}(T) = H^{\circ}_i(T) - H^{\circ}_i(T_{\mathrm{ref}}) \tag{5}$$

Specific entropy s $\left[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right]$:

$$\begin{aligned} s(p,T) = \frac{R}{M} \ln\left(\frac{n}{p} p_{\mathrm{ref}}\right) + \\ + \frac{1}{\rho} \sum_{i=1}^{N} n_i \left(S^{\circ}_i(T) - R\ln(n_i)\right) \end{aligned} \tag{6}$$

where R is the molar gas constant and $S^{\circ}_i(T)$ is the standard molar entropy of a component.

Specific heat capacity at constant pressure c_p $\left[\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right]$:

$$\begin{aligned} c_p(p,T) = \frac{1}{\rho} \left[\sum_{i=1}^{N} \frac{\partial n_i}{\partial T} \left(\Delta_f H^{\circ}_{i,T_{\mathrm{ref}}} + \Delta H^{\circ}_{i,T_{\mathrm{ref}}}\right) + \right. \\ \left. + \sum_{i=1}^{N} n_i C^{\circ}_{p,i}(T)\right] \end{aligned} \tag{7}$$

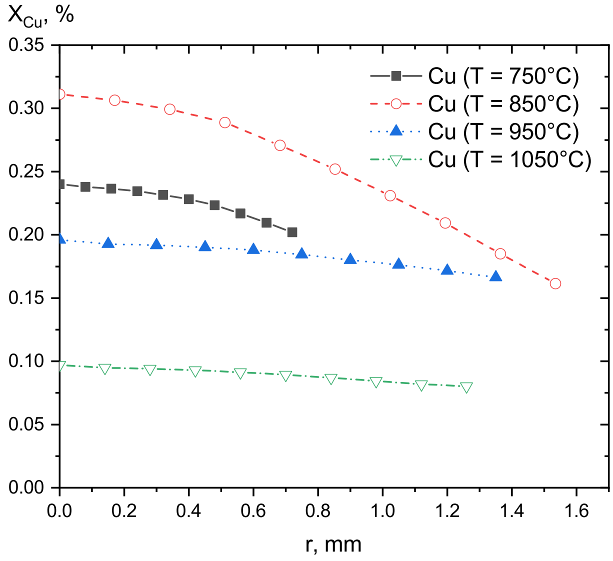

Figure 1. Radial distributions of copper vapour contents in plasma of arc discharges between Cu-W composite electrodes manufactured at temperatures of 750, 850, 950, and 1050°C

where $C^{\circ}_{p,i}(T)$ is the standard thermal capacity of the component.

The standard thermodynamic functions $\Delta_f H^{\circ}_{i,T_{\mathrm{ref}}}$, $\Delta H^{\circ}_{i,T_{\mathrm{ref}}}(T)$, $S^{\circ}_i(T)$ and $C^{\circ}_{p,i}(T)$ were taken from JANAF thermochemical tables [8] for $T_{\mathrm{ref}} = 298.15\,\mathrm{K}$ and $p = p_{\mathrm{ref}} = 1\,\mathrm{atm}$.

3. Results and Discussions

The radial distributions of contents of copper X_{Cu} and tungsten vapours X_{W} calculated from equilibrium plasma compositions of plasma of arc discharges between different types of Cu-W composite electrodes are shown in Figure 1 and 2, respectively. Results of the calculations of metal vapour content confirm the conclusions of the previous work [5], that sintering temperature used in manufacturing composite materials affects the total content of metal vapours admixtures in plasma and, consequently, the erosion resistance of the composite materials.

Based on the radial distributions of copper vapours shown in Figure 1, it is evident that the composite materials sintered at a temperature of 1050°C exhibit the highest erosion resistance, while those sintered at 850°C display the lowest. Since the temperature of 1050°C is very close to the melting temperature of copper (1085°C), it can be assumed that shock sintering at this temperature leads to partial melting of copper and, accordingly, an increase in its plasticity. This, in turn, contributes to a denser penetration of copper into the tungsten powder and a decrease in the porosity of the resulting product [6]. In addition, an increase in temperature contributes to better diffusion of the material, which also leads to a decrease in porosity.

Regarding the radial distributions of tungsten

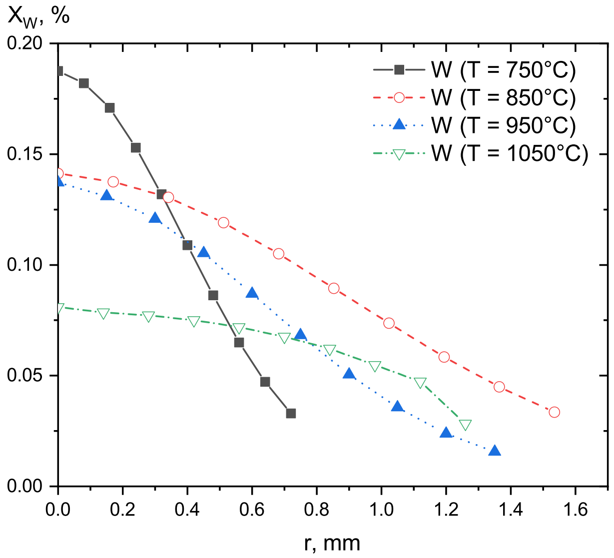

Figure 2. Radial distributions of tungsten vapour contents in plasma of arc discharges between Cu-W composite electrodes manufactured at temperatures of 750, 850, 950, and 1050℃

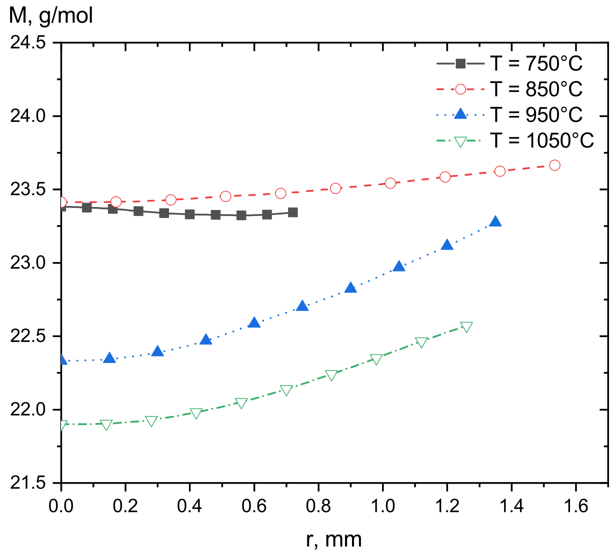

Figure 3. Radial distributions of molar masses of plasma of arc discharges between Cu-W composite electrodes manufactured at temperatures of 750, 850, 950, and 1050℃

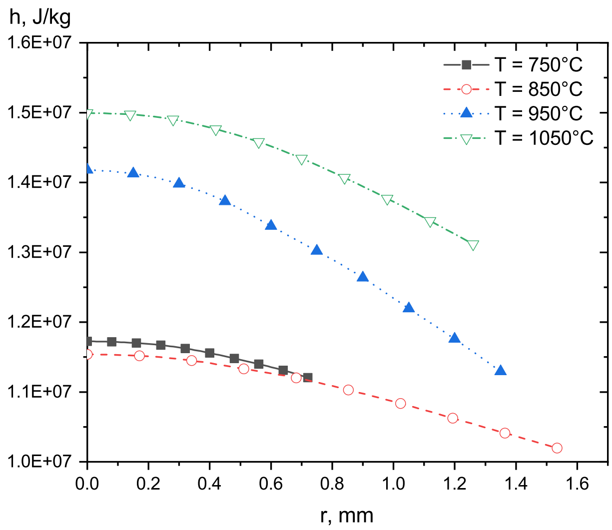

Figure 4. Radial distributions of specific enthalpy of plasma of arc discharge between Cu-W composite electrodes manufactured at temperatures of 750, 850, 950, and 1050℃

vapour contents (Figure 2), the conclusions are not as straightforward. On the one hand, it is evident that at the axis of the arc discharge ($r = 0$ mm), the amount of tungsten vapour in the plasma between electrodes with a sintering temperature of $T = 750$°C is higher compared to other types. However, as the distance from the axis increase, the amount of tungsten vapour for electrodes sintered at $T = 750$°C decreases significantly and becomes smaller in comparison to those sintered at 850, 950, or even 1050°C

Nevertheless, based on the radial distributions of metal vapours, it can be concluded that the discharge plasma between composites sintered at a temperature of 1050°C exhibits a lower concentration of electrode materials, suggesting a potentially higher erosion resistance of these materials.

The radial distributions of thermodynamic properties, namely molar mass, specific enthalpy and specific entropy, of discharge plasma between each type of electrodes are shown in Figure 3–5, respectively.

It is evident from Figure 3 that the radial distributions of molar masses of the discharge plasma confirm the earlier conclusions regarding the amount of metal vapours in the plasma. Considering that the molecular weights of copper and tungsten (63.6 and 183.8, respectively) are significantly higher than that of air particles, an increase in the molar mass indicates a higher concentration of material in the discharge gap. Consequently, it can be inferred that electrodes sintered at a temperature of 1050°C exhibit better erosion resistance, as the discharge plasma between such electrodes contains the least amount of electrode-origin material.

The radial distributions of specific enthalpies of the plasma, as depicted in Figure 4, provide insights into the efficiency of plasma heating. This information allows us to assess how effectively the electrodes dissipate heat and transfer it to the plasma, which ultimately contributes to their overall resistance. Based on Figure 4, it can be inferred that electrodes sintered at a temperature of 1050°C exhibit a more efficient plasma heating process. This suggests that these electrodes are better able to dissipate heat and transfer it to the plasma, thereby enhancing their resistance.

To assess the efficiency of plasma heating, it is necessary to relate the enthalpy to the total energy (power) dissipated in the arc discharge, which includes contributions from electrodes and plasma heating, radiation loses [9], etc. The typical values of arc currents I, voltage drops U, and calculated powers P

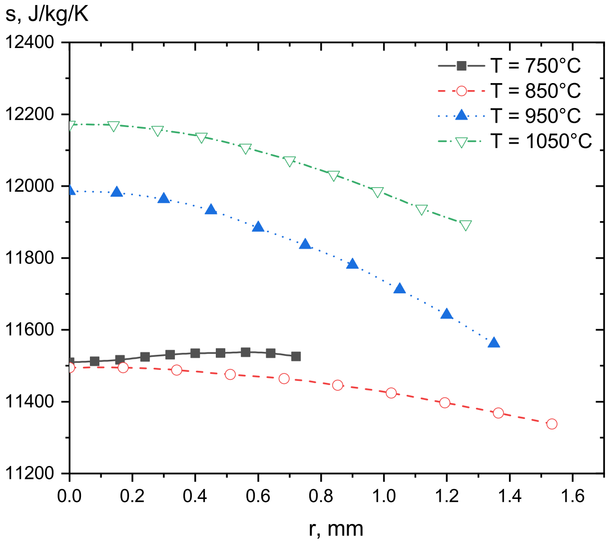

Figure 5. Radial distributions of specific entropy of plasma of arc discharge between Cu-W composite electrodes manufactured at temperatures of 750, 850, 950, and 1050℃

Electrode type	*I*, A	*U*, V	*P*, W
750°C	3.5	55	192.5
850°C	3.5	55	192.5
950°C	3.5	54	189.0
1050°C	3.5	65	227.5

Table 1. Typical values of arc currents I, voltage drops U and calculated powers P dissipated in discharge plasma between different type of electrodes

dissipated in the discharges between different types of electrodes are provided in Table 1.

It is evident that the highest dissipated power is observed for electrodes sintered at 1050°C, which aligns well with the radial enthalpy distributions. Furthermore, the calculated powers for electrodes sintered at 750 and 850°C are identical, while their radial enthalpy distributions exhibit negligible differences. In the case of electrodes sintered at 950°C, the calculated dissipated power matches that of the two previous types, but the enthalpy values along the radius are significantly higher.

Based on these observations, it can be assumed that the energy dissipation efficiency in the discharge between electrodes sintered at 950°C may be comparable to that of electrodes sintered at 1050°C. Although the energy transferred directly to the plasma shows insignificant differences, the power dissipated in the discharge is noticeably lower (189 and 227.5 W, respectively). However, as depicted in Figure 1–3, the electrodes sintered at 950°C exhibit slightly higher erosion compared to those sintered at 1050°C.

As seen from Figure 5 the radial distributions of entropy fully correlates with radial distributions of enthalpy (Figure 4). Therefore, since entropy reflects the efficiency of energy dissipation, preference should be given to electrodes sintered at 950 and 1050°C.

4. Conclusions

The plasma of electric arc discharges between electrodes manufactured of Cu-W composite materials at temperatures of 750, 850, 950, and 1050°C was investigated by optical emission spectroscopy technique.

It has been found that electrodes sintered at temperature of 1050°C have the smallest amount of material of electrode origin in the discharge plasma, indicating their better erosion resistance in comparison of other type of the investigated composite materials.

It is observed that electrodes sintered at 1050°C demonstrate the highest erosion resistance and energy dissipation efficiency. However, electrodes sintered at 950°C can also provide efficient energy dissipation while exhibiting slightly higher erosion. The results emphasize the importance of sintering temperature in the manufacturing process of Cu-W composite electrodes for electric arc discharges.

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