INVESTIGATIONS OF THERMAL PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN COMPOSITE Ag–C ELECTRODES

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The complex investigation of the arc discharge plasma between composite Ag–C electrodes in the range of 3.5 A…30 A currents was carried out. Plasma temperature in assumption of local thermodynamic equilibrium was obtained by optical emission spectroscopy. Electron densities were obtained from half-width of Ag I 466.8 nm spectral line in the assumption of dominating quadratic Stark effect emitted by plasma at arc current 30 A. Electrical conductivity and electron density in arc discharge plasma at current 3.5 A were obtained by solution of the energy balance equation. The results of investigations of plasma arc discharge between Ag–C electrodes were compared with parameters of discharge plasma between C–Cu electrodes at arc current 3.5 A.

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INTRODUCTION

It is well known, that powerful semiconductor electronics modules for large currents and voltages switching, as an alternative to mechanical contactors, are widely used. However, mechanical contactors are still used in electrical industry because of their simplicity, relatively low cost, significant resistivity to current and voltage overload, etc. In addition, sliding (mechanical) electrical contact still has no alternative for usage in electric vehicles [1].

On the other hand, it is known, that there is a short-time arc between contact groups occurs during switching of electric circuit with inductance. A similar situation is observed in the case of sliding contacts. This arc phenomenon is accompanied by erosion of material contact, which reduces the reliability and operating life of switching device. Investigations of parameters and state of arc discharge plasma with electrode vapour impurities will enable to understood better the erosion characteristics of the contacts. Moreover, it can be possible to develop specific recommendations for improving of the composition material. Such complex investigations of arc discharge plasma between composite C–Cu (80:20%) electrodes were carried out in [2]. This composite material was specially developed for sliding contact production for electric vehicle. The breaking arc discharge between contact pairs is often realised during vehicle movement. It was found by that the basic properties of such discharge plasma are defined wholly by vapours of electrodes' fusible components (copper, in this case).

Composite Ag–C (95:5 %) material is also used to produce the contacts of mechanical contactors. Silver in this composite material was used to provide necessary electrical conductivity of the contact. A small admixture of graphite prevents the welding phenomena of the contact group during circuit switching. Nevertheless, composite Ag–C material is widely used in low voltage contactors, there is no detail investigation of plasma properties of arc discharge, which occurs during switching between such composite electrodes, yet.

The aim of this study is the determination of parameters of arc discharge plasma between composite Ag–C electrodes. This study will be focused on the temperature, electric field strength, conductivity and electron density determination in such arc plasma. The results will be compared with plasma parameters of arc between composite C–Cu electrodes.

1. EXPERIMENTAL INVESTIGATIONS

1.1. ARC DISCHARGE ARRANGEMENT

The free burning electric arc was ignited in air between the end surfaces of Ag–C (95:5%) composite non-cooled vertically arranged electrodes. The diameter of the rod electrodes was 6 mm, the discharge gap was 8 mm and arc current was in a range 3.5 A…30 A. To avoid the metal droplet appearing a pulsing high current mode was used: namely, the rectangular current pulse up to 30 A was put on the "duty" low-current (3.5 A) discharge. The duration of this high-current pulse 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.

A more detail description of experimental setup is presented in [3, 4].

1.2. TEMPERATURE MEASUREMENTS

Plasma temperatures were obtained by Boltzmann plot method [4]. Spectral lines Ag I 405.5, 447.6, 466.8, 520.9, 768.8 and 827.4 nm were used in the determination of plasma temperature of arc discharge between Ag–C electrodes [4]. Spectral lines of Cu I 510.5, 515.3, 521.8, 570.0 and 578.2 nm were used in plasma temperature measurements in case of arc discharge between C–Cu electrodes [2].

1.3. ELECTRON DENSITY MEASUREMENTS

Electron densities were obtained from the half-width of spectral line Ag I 466.8 nm in an assumption of dominating quadratic Stark effect at arc current 30 A [4]. The spectral device, combined with Fabry–Perot

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interferometer in etalon mode, was used for registration of spectral line profiles [5] with spatial resolution.

1.4. ELECTRIC FIELD MEASUREMENTS

The determination of electric field in the positive column of arc was performed by technique based on modulation of discharge gap [6]. Interelectrode distance was varied periodically with a frequency of 25 Hz using a specially designed device (so called, electromechanical modulator). Consequently, the arc voltage contains the harmonics of frequency of 25 Hz. The amplitude of the first harmonic can be used to determine the electric field in the positive column of arc discharge plasma. The bandpass filter and the second-order discrete Fourier transform were used for measuring of this first harmonic amplitude. This technique allows measuring the electric field in real time mode.

1.5. CONDUCTIVITY AND ELECTRON DENSITY CALCULATION

The solution of energy balance equation is used to calculate the conductivity and the electron density of arc discharge plasma [2]. This method requires to determine preliminary the radial temperature distribution and the electric field in positive column of the arc discharge plasma.

2. RESULTS AND DISCUSSION

At the preliminary stage the radial temperature distributions in the range of 3.5 A…30 A currents were defined (Fig. 1). One can see, the increasing of current up to 10 A causes the expected rising of temperature at the arc axis and appropriate rising of arc channel width.

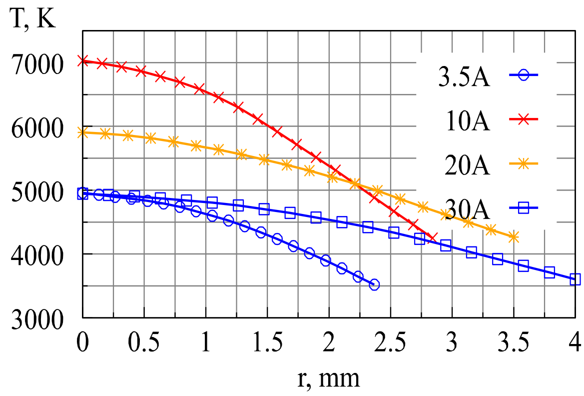

Fig. 1. Radial distributions of plasma temperature of arc between Ag–C electrodes

However, the further consistent increasing of arc current up to 20 A and 30 A causes the decreasing of temperature at the arc axis, although the arc channel is expanding. Such kind behavior of temperature is inherent to plasma of arc between Ag–C electrodes only. The explanation of this phenomenon, of course, requires further investigation.

The interferogram of Ag I 466.8 nm spectral line for the discharge current 30 A is shown in Fig. 2. It was noted previously, this spectral line is broadened mainly due to the quadratic Stark effect. The width of spectral line in different radial points was defined from this interferogram. The radial distribution of electron density, calculated from the width of this spectral line, is shown in Fig. 3. Unfortunately, this method can not be used to determine the electron density in plasma of arc discharge at arc current 3.5 A. This is because the width of the spectral line Ag I 466.8 nm is comparable with the instrumental contour of Fabry–Perot etalon. In addition, the radiation intensity of plasma was not sufficient for interferogram registration in this case.

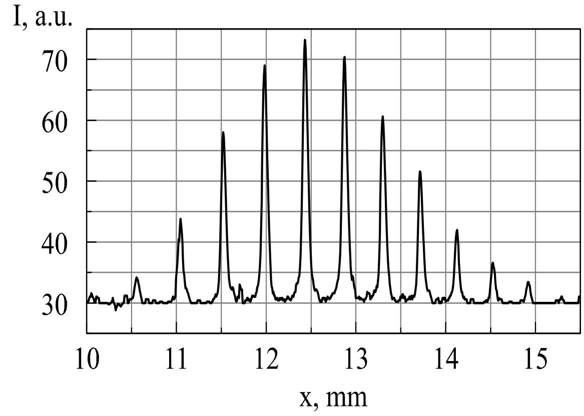

Fig. 2. The interferogram of spectral line AgI 466.8 nm, emitted by plasma at current 30 A

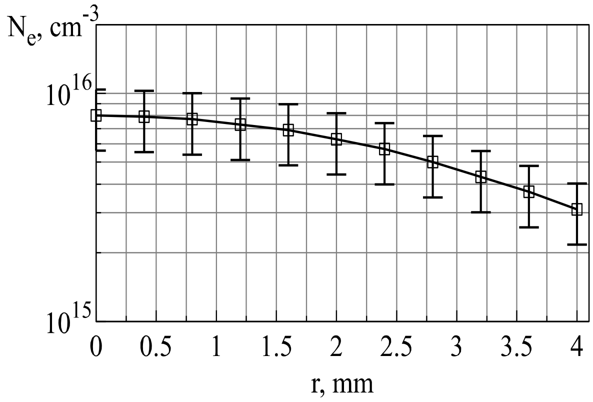

Fig. 3. Electron density of electric arc discharge between Ag–C electrodes at current 30 A

Therefore, the another kind technique to determine the plasma electron density in the arc discharge of 3.5 A between Ag–C electrodes was used. Namely, this parameter was determined by solution of the energy balance equation. Necessary for this method an electric field of positive column of arc was determined by modulation of interelectrode gap. The time dependence of this field is shown in Fig. 4. The field strength decreases and electric discharge tends to a steady state during 25 s after ignition of discharge. It is apparently this phenomenon is due to formation of oxides on the cathode surface. The value of electric field of approximately 3 V/mm is stable during the next time range of 75 s. Therefore, this value was used to solve the energy balance equation. The electric field starts to decrease again at the time point t=100 s. It is apparently such decreasing can be caused by a significant cathode melting and consequently increasing of metal vapour in the gap.

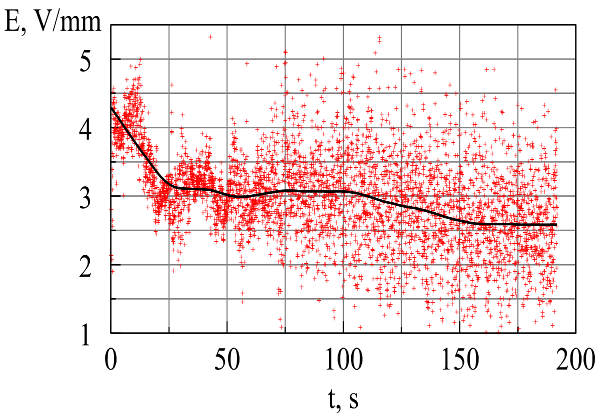

Fig. 4. Electric field in plasma of arc discharge between composite Ag–C electrodes at current 3.5 A

The radial temperature profiles in arc discharge plasma at 3.5 A current between Ag–C and, for comparison, C–Cu electrodes are shown in Fig. 5. These temperature distributions (T) are accompanied by appropriate curves of upper (T_{sup}) and lower (T_{inf}) limits of measurement error. One can see that plasma temperature in arc between Ag–C electrodes is lower, but its gradient is higher than in discharge between C–Cu electrodes.

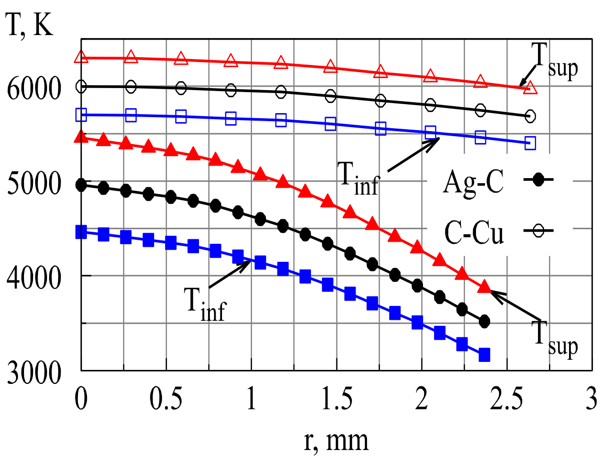

Fig. 5. Radial temperature profiles of electric arc between Ag–C and C–Cu electrodes at current 3.5 A

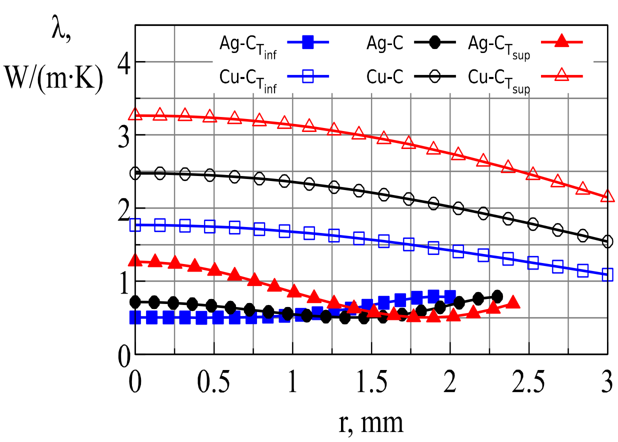

Fig. 6. Thermal conductivity of electric arc discharge between Ag–C and C–Cu electrodes at current 3.5 A

The thermal conductivity of atmospheric pressure plasma weakly depends on a concentration of the electrode material vapour according to the results of [7]. Therefore, the thermal conductivity of pure air was used in solving of the energy balance equation. The radial distributions of thermal conductivity of the arc discharge plasma between Ag–C and C–Cu electrodes are shown in Fig. 6. They correspond to those spatial temperature distributions, which are shown in Fig. 5. Radial distribution of thermal conductivity is non-monotone for the case of Ag–C electrodes. This phenomenon can be explained by the maximum of the reactive component of the thermal conductivity in the point of the temperature T=3600 K due to the dissociation of oxygen.

At the next stage, the electrical conductivity of plasma was determined by a solution of the energy balance equation on the base of experimentally obtained temperature distributions (Fig. 5) and the thermal conductivity (Fig. 6) in plasma. Because of non-monotone behaviour of the thermal conductivity, the radial distribution of electrical conductivity has also the non-monotone region as a result of solution of energy balance equation (Fig. 7). That is why, the electron density distribution, obtained from the electrical conductivity, has also non-monotonic region in case of Ag-C electrodes (Fig. 8).

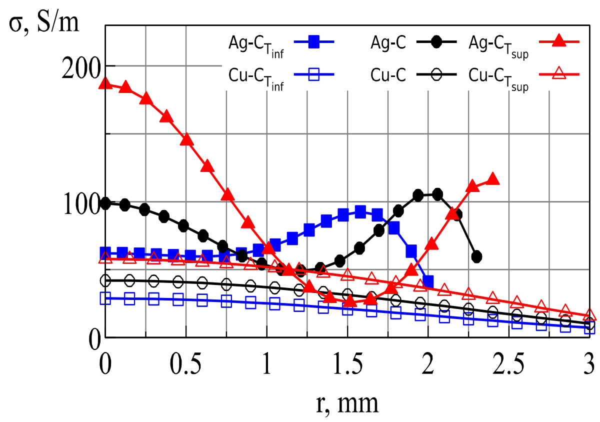

Fig. 7. Conductivity of electric arc discharge between Ag–C and C–Cu electrodes at current 3.5 A

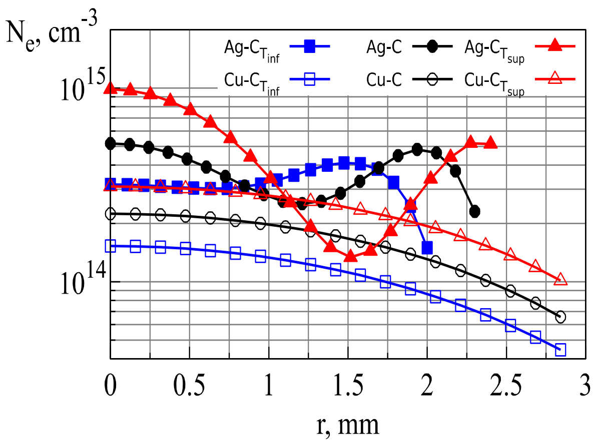

Fig. 8 Electron density in plasma of arc discharge between Ag–C and C–Cu electrodes at current 3.5 A

CONCLUSIONS

The technique of electric field measuring of arc discharge plasma in real time mode by modulating of gap length was developed. Obtained in such a way values of electric field allowed to calculate the conductivity and, respectively, the electron density in plasma by solution of energy balance equation. It was found that electron densities in plasma of arc discharges between Ag–C and C–Cu are comparable. The calculated value of electron density of arc discharge between Ag–C electrodes for arc current 3.5 A has minimum at distance from the arc axis r = 1.2 mm, which can be explained by extremum of reactive component of the thermal conductivity owing to dissociation of molecule O_2 at the temperature T=3600 K.

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ИССЛЕДОВАНИЕ ТЕРМИЧЕСКОЙ ПЛАЗМЫ ЭЛЕКТРОДУГОВОГО РАЗРЯДА МЕЖДУ КОМПОЗИТНЫМИ Ag–C ЭЛЕКТРОДАМИ

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Выполнено комплексное исследование плазмы электродугового разряда между композитными Ag–C электродами в диапазоне токов 3,5…30 А. Методом оптической эмиссионной спектроскопии определена температура плазмы в предположении локального термодинамического равновесия. Электронная концентрация плазмы электродугового разряда силой тока 30 А определена по уширению спектральной линии Ag I 466,8 нм. Электропроводность и электронная концентрация плазмы дугового разряда силой тока 3,5 А определены путем решения уравнения энергетического баланса. Результаты исследований плазмы дугового разряда силой тока 3,5 А между Ag–C электродами сравнивались с параметрами плазмы разряда между C–Cu электродами.

ДОСЛІДЖЕННЯ ТЕРМІЧНОЇ ПЛАЗМИ ЕЛЕКТРОДУГОВОГО РОЗРЯДУ МІЖ КОМПОЗИТНИМИ Ag–C ЕЛЕКТРОДАМИ

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Виконано комплексне дослідження плазми електродугового розряду між композитними Ag–C електродами в діапазоні струмів 3,5…30 А. Методом оптичної емісійної спектроскопії визначено температуру плазми у припущенні локальної термодинамічної рівноваги. Електронна концентрація плазми електродугового розряду силою струму 30 А визначена із ширини спектральної лінії Ag I 466,8 нм. Електропровідність та електронна концентрація плазми дугового розряду силою струму 3,5 А визначені шляхом розв'язку рівняння енергетичного балансу. Результати досліджень плазми дугового розряду силою струму 3,5 А між Ag–C електродами порівнювались з параметрами плазми розряду між C–Cu електродами.