doi:10.14311/ppt.2019.2.123
Plasma Physics and Technology **6**(2):123–126, 2019

ANALYSIS OF EROSION RESISTANCE OF CuC ARCING CONTACTS MANUFACTURED BY PLASMA SPRAYING TECHNOLOGY

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Abstract. Results of the erosion resistance study of the CuC electrodes manufactured by plasma spraying technology are presented. The diagnostics has have been performed by means of high-speed camera technique and optical emission spectroscopy which has been synchronised with electrical diagnostics. After the load material analyses, namely determination of mass loss and analysis of micro sections, have been done. It has been found that the erosion rate depends on conditions applied for the formation of coating layer, which was deposited either in air or in argon plasma. Furthermore, the erosion rate is significantly lower in the case of air plasma spraying.

Keywords: electrode erosion, low-voltage circuit breaker, coating.

1. Introduction

An increase of the lifetime of the low-voltage high-current switching devices (LVSD) requires the guaranty that the arc transfers from the main contacts to arcing contacts. One of the main factors affecting the erosion of arcing contacts during arc burning are plasma jets [1], which starts from in the arc roots [2]. The arc movement under the action of electromagnetic forces can be analysed both by experiment and modelling. Modern research relies on mathematical simulation due to the complexity of experimental analysis of the processes occurring inside the switching devices. When analysing the arc movement in a switching device, several aspects have to be addressed: position of the moving contact, influence of the arc chamber material [3], arc forces [4], contact erosion, arc power and the position of the arc in the arc chamber [5]. Furthermore, the behaviour of the electric arc depends on the electrode surface material, electromagnetic blowing conditions and electrode material composition.

The circuit breakers use contact systems with additional arcing contacts with better erosion resistance than the main contacts. At the same time, the arc moves along the surface of the arcing contacts toward the external elements of the arc chamber. The arc duration in DC and AC circuit breakers does not exceed 10–12 ms, so arcing contacts covered with a layer (or overlays) of erosion-resistant materials can be used. Erosion-resistant coating can be formed by plasma spraying using the copper-based composite materials in argon or air.

Promising materials for use in the arc contacts of low voltage circuit breakers are copper based composite materials. Various alloys have been proposed with refractory metals [6] or graphite as LVSD contact materials. In particular, in studies of the erosion of tool electrodes, an analysis of CuCr, CuMo, CuW and CuC alloys was carried out [7]. The analysis demonstrated a high erosion resistance in the cited materials. According to [7], composites using graphite showed the best erosion properties. In this case material porosity also contributed to that effect, in addition to refractory phase content. It should also be noted that the electron output energy of graphite is higher than that of copper [8]. This can have a significant impact on the behaviour of the arc at the arc roots, in particular, to improve the transition of the arc from the main contact to the arcing contact.

When an arc is burning between the breaker contacts, specific areas of material ejection from the surface and plasma jets can be distinguished [2]. The main causes of arc contact wear are: evaporation triggered by arc burning, splashing of metal as a result of explosive processes, removal of molten droplets by external forces. Plasma jets significantly affect arc contact wear and have a significant role in all of these processes. Therefore, the analysis of plasma jet behaviour is relevant for finding ways to reduce the erosion of LVSD contacts. The formation and development of plasma jets and some other processes in an electric arc depends on spatial distribution of temperature, current density, mass flow and energy.

The increase in erosion resistance of circuit breaker arcing contacts requires solving a set of problems. In this article only the influence the conditions of plasma coating formation on electrode erosion is considered. The analysis of the behaviour of plasma jets emerging from arc roots is also provided.

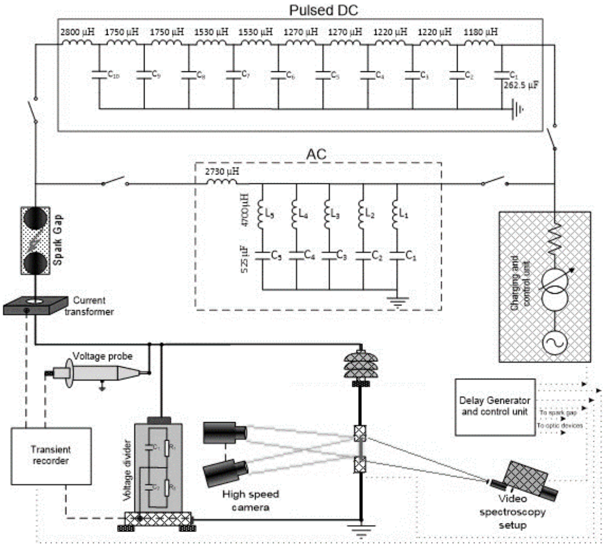

Figure 1. Principal scheme of experimental setup [9].

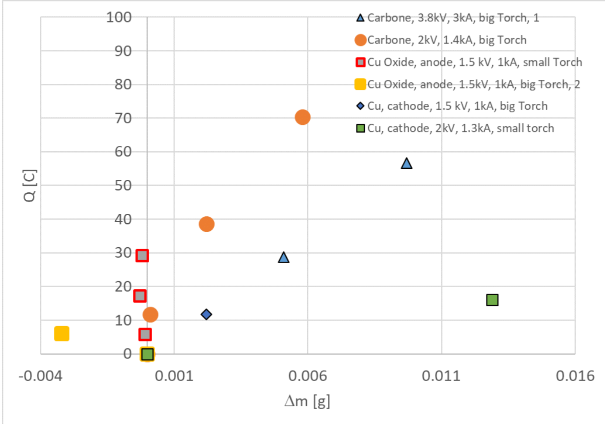

Figure 2. Mass loss Δm of various electrodes with different coatings in dependence on transferred charge Q. Parameters of electrode load (current and voltage) are given in the legend.

2. Experimental setup

The principal scheme of experimental setup is shown in Fig. 1. Detailed description of the current source and diagnostics is given elsewhere [9]. This setup provides both AC pulsed DC waveforms at the current level below 5 kA and DC duration up to 20 ms. In the present experiments the current was restricted to maximum 3 kA and the arc duration was about 10 ms. The setup was extended by high-current diodes in order to restrict the polarity of load current.

Several electrode prototypes were studied: uncoated copper electrode, electrode with CuC coating in argon and electrode samples obtained using different fractions of CuC (95/5 by volume) powder material deposited in air plasma. A feature of the last electrodes is a high content of copper oxides in the coating.

The electrodes were loaded by current in ambient air. Besides the electrical measurements, spectroscopy setup was used to register the arc radiation spectrum and a high speed camera has supplied the arc images.

3. Results and discussion

3.1. Analysis of electrode erosion

The value of electrical erosion has been characterized by the mass loss under given experimental conditions.

The electrodes were arranged vertically (see Fig. 1) for the purpose of electrode erosion analysis for different coatings and recording of plasma jets dynamics. Each test electrode with different coatings was always used as the top electrode. The bottom electrode was a CuW (80/20) electrode in the form of a hemisphere of significantly larger diameter. This material was used in order to reduce the material transfer from the bottom electrode.

Figure 2 shows the analysis of the mass loss depending on the transferred charge for electrodes with copper-graphite coatings deposited in argon (marked as «Carbon» in the figure) and in air (marked as «Cu Oxide» in the figure).

The largest mass loss was registered for uncoated copper electrodes. It amounts to about 12 mg after a charge transmission of about 20 C. The electrodes coated with CuC have shown high erosion resistance at currents below 1.4 kA. The mass loss was less than 4 mg at transmitted charge of more than 70 C. However, at higher currents (3 kA) a significant decrease in erosion resistance is observed. Thus, value of Δm was about 9 mg at a transferred charge of about 55 C. The best erosion resistance has been achieved by the electrodes coated in air plasma environment. These electrodes have high levels of oxides in their coating. An electrode with a similar coating when used as a cathode at a current of 1 kA showed an insignificant (up to 4 mg) increase in mass, probably due to the condensation of gaseous copper released from the anode surface. When the current value was raised a slight increase in erosion was observed.

The analysis of photographs of electrodes and micro sections has shown significant surface damage for the electrodes coated in argon. The electrodes coated in an air plasma environment have greater amount of gas inclusions inside the coating. However, these inclusions do not show such a significant expansion as for electrodes made in argon. For any type of spraying, detachment of this coating from the electrode is observed, which is an adverse factor that significantly reduces the reliability of electrodes with similar coatings. In future, it is necessary to consider the possibility of using a substrate for spraying to improve the bond between electrode materials and coating.

3.2. Analysis of plasma jets

The occurrence and development of plasma jets in an electric arc depends on the spatial distribution of temperature, current density, as well as on mass and energy flow.

In high-current arcs with plasma jets the temperature reaches its highest value at the points close to the arc root. Acquired arc spectra have been analysed using the basic data from [10]. The arc temperature was estimated by Boltzmann plot for the electrodes with different coatings. The analysis shows that the average arc temperature close to the electrode surface with a CuC is about 3000K higher than that for pure copper electrode. This difference may arise from the higher energy of electrons leaving the surface. Furthermore, in case of a copper electrode without powder coating the amount of metal vapour is much larger. This can also reduce the arc temperature.

The simplified equation that describes the energy balance in a DC arc with plasma jets reads [2]:

$$\nabla \cdot (\mathbf{j}\phi - \lambda \nabla T + h\rho \mathbf{v}) = 0 \tag{1}$$

Here $\mathbf{j}$ is the current density, ϕ - potential, λ - thermal conductivity, T - temperature, h - enthalpy, ρ - density, $\mathbf{v}$ - plasma velocity.

Three components of the energy flow are Joule heating, heat conduction and energy brought by mass inflow. In the case of stationary arc the velocity of the particles depends on the location of the particles in the arc. It has a maximum in the near-electrode region and decreases for the positions away from the arc axis. Furthermore, the particle velocity is influenced by the output energy of the particles, which they gain leaving the electrode surface. Particle motion are attributed to electromagnetic forces and thermal processes in the arc. The directed plasma jets create an injection effect and draw electrode material into the arc.

Thus, the energy and temperature of the arc depend on the current density and the applied potential and on the characteristics of the electrode material. As it follows from Eq. 1, an increase in the flow velocity in a plasma jet will lead to a growth of temperature assuming a constant current density and thermal conductivity.

The parameters of plasma jets between opposing electrodes depend on the location of the electrodes, the distance between them, their materials and current characteristics.

The major reasons for arcing contact wear of high-current switches are metal evaporation under the action of energy released at the contacts or in the arc; metal spraying as a result of accelerated melting, explosive processes and gas evolution; removal of melted droplets by various external forces.

When the arc is burning between two spherical surfaces, the anode and cathode plasma jets are directed not strictly aligned, but in a certain angle to each other due to the action of electromagnetic forces acting on the jets. In this embodiment, a portion of the arc is supported by plasma jet instead of electrodes.

The mass loss of the electrodes caused by plasma jets strongly depends on metal melting temperature and evaporation. In some cases described below a mass increase was found instead of mass loss. A possible reason is that the coating components partially have a high melting point and do not evaporate under the action of a plasma jets, but rather condense the copper vapour from incoming flux.

Various jet shapes should be considered in the study of evaporation of various materials. When analysing high-speed images of arc burning on a copper electrode a large amount of ionized gases surrounding the jet can be seen. A similar phenomenon is not observed on electrodes with an arc-resistant coating.

The lengths and diameters of the jets also depend on the characteristics of the electrode coatings. Materials with higher electrical conductivity, thermal conductivity and low boiling point create plasma jets of larger length. Copper is also characterized by a longer anode jet. When testing the copper-graphite electrodes over the copper hemisphere (Figure 3), the upper jet of CuC dominates independent on electrode polarity. The reason of such behaviour is, first, due the smaller radius of coated electrode and secondly, graphite has a higher electron output energy comparing to copper.

Figure 3 shows the behaviour of an alternating current arc when testing an electrode with a copper-graphite coating. Initially, the development of the arc (frames 1–4) can be distinguished, then the plasma jets starts to move along the surface of the lower electrode, the cathode, and the anodic jet deviates in the opposite direction (frames 3–5). The arc length increases and its resistance grows, and ionized gas with high conductivity take the previous arc position. A new jet occurs on the surface of the cathode near the anode jet. Anode and cathode jets attract to each other (frames 5–7). After this instant the arc stretches again stretching (frames 9–11) up to the instant of current zero crossing, when the plasma disappears (frame 12). After the arc re-ignition, which is caused by the presence of residual conductivity in the electrode gap filled with ionized gas (frames 13–16) the jets are formed again.

Figure 3 also shows that after the current passes through zero and the upper electrode becomes an anode, smaller anode jets occurs, which indicates a change in the intensity of the output of the electrodes. However, since the diameters of the electrodes are not the same, the dominant jet always develops from smaller electrode, regardless of polarity and electrode material.

The arc ignites with nearly coaxial anodic and cathodic jets. With increasing current the jet length also increases and the jet tips shift toward the lateral side away from each other. The anode jet becomes dominant when the current enhances. This process is accompanied by a sharp increase in erosion caused by the thermal and dynamic effects of the anode jet. When the anode jet reach the cathode its tip spreads and suppress the cathode jet. The anode jet promotes the cathode melting and splashing of molten metal. In such a situation the erosion of small electrode is

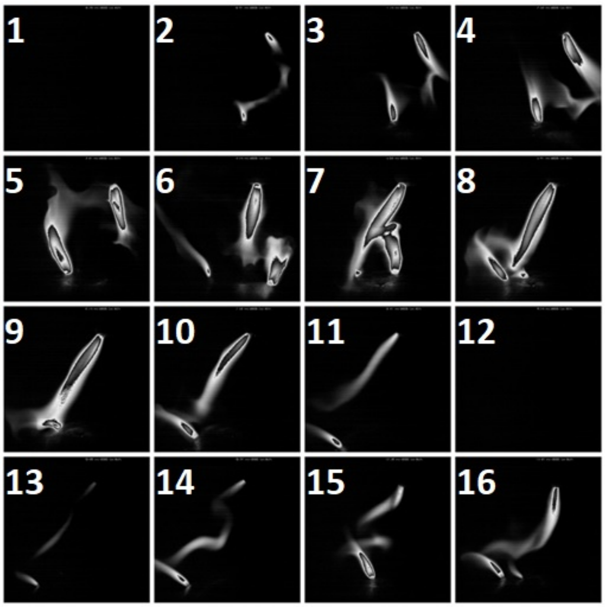

Figure 3. Arc images in case of copper-graphite coating. AC operation with $I_{\max} = 1.4\,kA$, voltage of $2\,kV$.

mainly determined by the metal evaporation, while the ablation processes prevail in erosion of big electrode.

During the research of various coatings, characteristics of plasma jets for each coating were identified. In the case of copper electrode well visible metal vapour of evaporating metal, which indicate both the erosion of the test electrode and the subsequent contamination of the surface of the opposite electrode by deposited copper was registered. Copper-graphite electrodes coated in the argon environment shows the highest jet intensity, which is associated with an increased electron energy during the graphite evaporation. The electrodes, which provide the lowest erosion were coated in an air environment, have less intense plasma jets.

It should be noted that the movement of the arc along the surface of the electrodes of various materials was almost the same. However, in addition to the coating material, the intensity of the jets was significantly affected by the characteristics and polarity of the applied current.

Further research is necessary to analyse the dependence of the jet intensity on electrode polarity.

4. Conclusions

The erosion behaviour of various coatings which can be applied for arcing contacts of high-current circuit breakers was analysed. It has been found that the contacts with a coating deposited in an air plasma environment, i.e. having a large amount of copper oxides, show higher erosion resistance. The analysis of the behaviour of plasma jets emitted from the surfaces of the electrodes was carried out. The most intense jets were observed from the surface of copper-graphite coatings deposited in argon. The dependence of the intensity of the jets on the strength and polarity of the applied current is analysed. The analysis of the movement of plasma flows along the electrode surface was carried out. For further analysis of the behaviour of plasma flows, it is necessary to carry out studies using electrodes of various configurations, since the radius of the «lower» electrode had a significant impact on the characteristics of plasma jets. The plasma jets on the electrodes with a copper-graphite coating have a higher temperature in the near-electrode area.

Further research is planned for analysis of the influence of oxides on the behaviour of the jets and erosion dependence on the coating structure.

Acknowledgements

The authors from INP thank miss Uta Haeder-Schhult for valuable technical support in preparation and analysis of micro sections.

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