Dependence of the plasma composition in the low-current vacuum arc discharge on CuCr cathode on the current value and surface conditions

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Abstract. The dependence of the ion flux mass-charge composition from the vacuum arc plasma with the CuCr cathode on a value of the discharge current was investigated via the Thomson spectrometer with automatic signal registration and analysis. The microsecond arc was formed in a millimeter gap between CuCr cathode and copper anode under high vacuum conditions. The arc current was changed within the range from a few to tens of ampere. At the highest currents the plasma composition corresponded the elemental composition of the cathode surface. The fraction of the chromium ions significantly decreased with the arc current decreasing below 30 A. There was noticeable increasing of the fraction of the chromium ions in the plasma at the discharge currents near the threshold values for the cathode materials. The effect appeared on coarse-grained non-melted cathode surfaces, and vanished after a multiple arcing.

1. Introduction
Wide application of copper-chromium composites in high-current vacuum interrupters necessitates detailed investigations of peculiar properties of vacuum arc discharges on such types of cathode materials with a complex surface structure. Particularly, generation of emission centers on the two-component surface remain understudied. Data about the generation of the emission centers are important for simulation of vacuum arc discharges in course of development of electrical devices. Additionally, the data can be helpful for the solving of the fundamental problem of investigation of the cathode spot operation in vacuum discharges, since the components of the composite material have different thermodynamic, ionization and other properties. The properties can influence the emission center operation. And the influence can lead to variation of comparatively easy observable parameters such as the discharge plasma charge state composition. The analysis of the discharge plasma elemental composition allows estimation of specific erosion of the composite electrode components.

At the moment, there are investigations that show a corresponding of vacuum arc plasma composition to the CuCr cathode material elemental composition at the discharge currents about 500 A [1]. And also there are investigations of low-current vacuum arcs which demonstrate a tendency of cathode spots to appear mostly on the chromium grains when the grains are sufficiently large, and absence of the tendency when the grains size is in nanometer range [2, 3]. From this fact a hypothesis of the prevalence of the chromium ions in the low-current vacuum arc plasma on the CuCr cathode
and the equivalence the chromium ion fraction to the chromium material fraction in the cathode at the higher currents was derived.

An attempt to obtain a dependence of the ion flow composition from the vacuum arc plasma on the discharge current was made in present work. The vacuum arc cathode was made of CuCr composite material. And the discharge current values were in range from units to tens of ampere. First experiment, described in more details in [4], gave contradictory results. And the problem demanded more thorough study.

2. Experimental setup

Most of the plasma source elements were identical to the plasma source in experiment with copper cathode [5]. The scheme of the plasma source is given in figure 1. The hollow anode of about 300 cm³ in volume had a copper disk input which was placed at 0.7 mm distance from the cathode. There were also some igniting tungsten needle electrodes in this gap. The distance between them and the cathode was about 100 µm. The arc ignition was performed by the plasma from the igniting discharger. At the moment the LC-line pulse reached the cathode the igniting gap voltage exceeded the breakdown voltage and the discharge of the auxiliary capacitor with the capacitance of 250 pF was triggered. The arc discharge plasma ions accelerated in the gap between the hollow anode exit grid exposed to the voltage of 3 kV to ground and the grounded grid. After that they reached a Thomson spectrometer through a collimator.

![Figure 1. Scheme of the plasma source with electrostatic gate. A - anode entrance ring; Tr – trigger electrode; K – cathode; R lim – limiting resistor, G – gate; C – collimator, F – field tips of the spectrometer discriminator, D – particle detector with the microchannel-plate amplifier, phosphor screen and CCD-matrix.](image)

Similar to the early experiment [4], the current pulse source was a LC-line. However, in this work the line consisted of eight sections with a 3.4 nF capacitor, and a 20 µH solenoid in each section. Effective duration of the quasi-rectangular pulse produced by the line was about 3.5 µs. The duration was longer than in first experiment (2 µs) [4]. It could increase a total plasma quantity, and therefore increase a signal intensity on the detector screen. The discharge current was varied by the limiting resistor. The resistance was ranged from tens of Ω to a few kΩ. The arc current value was measured by the inductive sensor with computer signal integration. An example of the current pulse waveform at the limiting resistance of 75 Ω is presented in figure 2.

The experiment was carried out in high vacuum conditions at 10⁻⁶ Pa. The cathodes were made of technical CuCr³⁰ from the interrupter ZKTD 630 made by Wuhan Feite Electric Co. Ltd. In the course of the study two samples of CuCr material were used. The samples were treated with a polishing paper with 50 µm grains. And one of them (sample 1) was next treated with a polishing paste with 20 µm abrasive grains. The sample 1 was previously used in the experiment [4]. After the polishing the samples were cleaned with an ethanol. All the experiments in the current study were started with cathodes not exposed to arcing. The spectrometer adjustment procedure was minimized (less than...
twenty arc ignitions at the minimal current value of 2 A). And the current starting value was chosen to be the lowest possible to reduce an impact of the erosion on the selection of the arc attachment point in a single cell mode of the cathode spot. Thus the cathode surface had low arcing influence before the experiment.

Figure 2. Arc current waveform obtained by integration of inductive sensor signal.

As opposed to the experiment with copper cathode [5], this investigation was aimed to obtain total signal of cathode material ions as accurate as possible for subsequent comparison. Thus the using of the electrostatic gate could distort the result. Chromium ions have lesser mass and higher velocity than the copper. When some Cu ion reached the gate at the end of the gate closing pulse, the Cr ion generated simultaneously with the Cu ion reached the gate earlier, when the gate, closed at the arc ignition moment, is still not open. And therefore a cut-off part of Cr ions could be sufficiently larger than the Cu part. For example, in case of the ion energy in range of tens of electronvolts the cropped signal part difference between copper and chromium ions could reach tens of percents. Therefore the gate was disabled. There was no possibility to cut off the plasma of the trigger discharge without the gate. Hence a tungsten was chosen as the trigger material instead of copper, to not distort the result signal by the additional copper ions.

The investigation of the mass-charge composition was carried out with the improved Thomson spectrometer with automatic signal registration and digital analysis. The quantitative assessment methodology was based on summation of the phosphor screen glowing intensity in the areas corresponding to the field deflection of the selected ion flow components with different mass-to-charge ratio ($M/Z$). The methodology is described in more detail in [6]. The summation was carried out on the images obtained by the CCD-camera, and the level of the matrix background noises was deducted from the signal level. As the copper and chromium ions have quite similar $M/Z$ ratios, to enhance the spectrometer resolving power within the range of $M/Z$ from 10 to 70, the optimal discriminator fields deflected the ions with $M/Z < 10$ outside the particle detector border. Therefore, the contaminating materials ions were not included into the analysis. Cu$^{4+}$ ions were also excluded from the analysis as their signal was not possible to distinguish from the O$^+$ having the same $M/Z = 16$ ratio value. Since even the percentage of Cu$^{3+}$ ions in the aggregated cathode material ion flow did not exceed 1.5% in the experiment, than the contribution of Cu$^{4+}$ would not be significant at all.

The arc current varied discretely with a limiting resistance variation from a series to a series of ignitions. In different experiments the sets of arc current values could differ from each other. However, all of them were in range from 2 to 80 A. Between 80 and 100 images with the ion signal were obtained for each arc current. The experimental data stated below are the result of the averaging of the obtained images.

3. Results and discussion
The experiment 1 data, presented in figure 3, were rather confusing. They not corresponded neither low-current investigations results [2, 3], nor high-current results [1], since the measured plasma
composition could not indicate the chromium fraction increasing at the low-current range, and could not correspond the assumed chromium-to-copper ratio in the CuCr30 material.

Figure 3. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Experiment 1, sample 1.

The surface analysis of the sample 1 was made via the scanning electron microscope LEO 982 with EDS analysis by Oxford Instruments software. The analysis result, presented in Table I, shows that the chromium fraction could be significantly higher than 30%. This element fractions could arise from the polishing treatment of the surface, when the copper, being more soft material than chromium, was removed from the surface much easier. It can be seen that copper and chromium ion fractions in the plasma at 50–80 A currents were close to the values in table 1. Therefore the data received in the first experiment not contradict to the results of investigation [1].

Table 1. Results of the surface analysis of the sample 1. Surface analysis of the sample made by means of the scanning electron microscope. The sum of Cu and Cr atoms were taken for 100%. Non-metallic surface inclusions were not taken into account in the result.

| Element   | Weight (%) | Atom (%) |
|-----------|------------|----------|
| Chromium  | 51.3       | 56.3     |
| Copper    | 48.7       | 43.7     |

Another few experiments were carried out to verify the contradiction between the data obtained in the experiment 1 and a hypothesis of the chromium ion prevalence in the ion flow at the very low arc current. In the experiment 2 the sample 2 was used as a cathode. In the experiment 2 averaged arc currents of 2, 4, 8, 14, 25, 40, 60 A were used. In the first part of the experiment 2 this currents were employed in ascending order (part 1). The result of the received data processing is presented in figure 4. And after the first series of arcing, the same values of current were employed in descending order (part 2). In both parts of the experiment 2 up to 100 frames were also obtained at each current value. The result of processing of the data is presented in figure 5.

It can be seen that the copper and chromium ion fractions were almost independent on the current in the high current range (few tens of ampere). And apparently the fractions could correspond the elemental composition of the sample surface. There is again the difference between the data and the assumed elemental composition of the CuCr30. However, the difference is less than in the case of sample 1. The sample 2 in contrast to the sample 1 was not subjected to the second stage of polishing. The inequality of the plasma composition in high current range in the experiments with these two
samples could indirectly indicate the polishing effect on the elemental composition of the CuCr surface. Unfortunately, the measurement of the sample 2 surface elemental composition was not performed.

![Figure 4. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Experiment 2, sample 2, part 1, ascending current values.](image1)

![Figure 5. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Experiment 2, sample 2, part 2, descending current values.](image2)

The copper ion fraction in the arc plasma significantly increased with the current decreasing below 30 A; and the chromium ion fraction correspondingly decreased at the same time. This variation is noticeable in the dependences obtained in the both parts of the experiment 2 (ascending and descending current). However, in the first part of the experiment 2 (ascending current) there was a chromium fraction peak at the minimal currents (see figure 4), when the quantity of cathode spot cells tended to one. The erosion of the cathode surface in the corresponding discharges was minimal. The chromium ion fraction of the in this case was even slightly larger than in high current range.

The experiment 3 was carried out to test a repeatability of the feature. The sample 1 was used as a cathode. However, a clean part of the cathode surface without the arc traces was placed in the discharge area under the trigger electrode. In the experiment 3 averaged arc currents of 2.5, 6, 9, 16, 30, 50, 75 A were used. And the values were employed only in ascending order. The result of
processing of data received in the experiment 3 is presented in figure 6. It can be seen, that the dependence obtained in the experiment is qualitatively similar to the dependence presented in figure 4. The copper and chromium ion fractions at high currents had a larger difference to the assumed ratio of the elements in the CuCr30. However, the fractions are close to the result of the sample 1 surface analysis (see table 1). Probably, it is possible to obtain the arc plasma ion composition corresponding to actual elemental composition in the bulk of CuCr30. However, it was hardly possible to melt a thick layer of the cathode material with current pulses which amplitude not exceeded 100 A, and pulse duration was in microsecond range. The thin layer available for melting in our setup had a distorted elemental composition affected by the polishing treatment.

![Figure 6. Aggregated percentages of copper and chromium ions in the registered cathode material ion flow depending on the arc current value. Experiment 3, sample 1, ascending current values.](image)

In the experiment 3 results the chromium ion fraction in the plasma at arc currents about 10 A was lower than the surface chromium elemental fraction. And the chromium ion fraction was again higher than the surface fraction at the lowest current. The absence of the chromium fraction peak at lowest currents in the experiment 1 [4] might be caused by the sample contamination before the experiment and the arc initiation on the dielectric inclusions. And the effect of increasing of the chromium ion fraction in the arc discharge plasma on the cathode with large chromium grains was proved to be repeatable.

During the experiment 2 the sample was treated by the multiple arcing. Given the total passed charge during the first stage of the experiment 2 about 0.06 C, the ion erosion rate for copper about 40 µg·C⁻¹ [7], and the cathode area subjected to arcing about 3 mm² we could estimate the thickness of the removed cathode material layer more than 100 nm. Thus the arcing was sufficient to remove the surface contaminations; and the result obtained with descending currents was made with cleaned cathode. Since the chromium ion fraction increased with the discharge current in range 8–30 A in all the experiments, independently of the cathode surface condition, then the small chromium ion fraction at the low current and increasing of the fraction with current were the features of the arc discharge for these experiment parameters. This feature assumed to be a background for the chromium ion fraction peak at the lowest current, which appearance apparently depended on the cathode surface conditions.

4. Conclusion
The results of the study show, that the plasma composition behavior is not accidental for the material. Generally, the obtained data show the increasing of the chromium ion fraction in the arc plasma at the currents near the threshold current value, when the cathode not undergo a significant surface melting. Further, the data show the absence of the increasing when the cathode is treated by the multiple arcing
(about a thousand arc discharges with current values in range of tens of ampere). This fact can indicate a correlation between the arc ignition areas and large chromium grains on the CuCr surface at the low discharge currents. The correlation was discovered in [2, 3].

However, at current values in range 10–30 A the plasma composition tends to have significantly more copper ions independently on the surface conditions. At the currents higher than 30 A the plasma composition apparently corresponds the elemental composition of the cathode material, at least the composition of the surface layer.

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