Investigation of Conductivity and Surface Structure of the Circuit Breakers Sidewalls

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Abstract – The circuit breakers sidewalls conductivity is measured and it was found that the resistance of exposed to arc areas demonstrates unusual dependence as function of temperature $R(T)$. Namely, the resistance shows non-monotone $R(T)$ dependence with maximum at 120–140 °C. Long term heating and cooling cycles resulted in systematic increase in R. The model taking into account the possibility of different types of conductivity of the samples (metallic as well as semiconductor types) was proposed. It was suggested that small metal bridges between metal droplets that can be destroyed during sample heating are responsible for the systematic R increase with a number of a cycle. The model succeeded to explain experiments both qualitatively and quantitatively. Direct microscopic measurements confirmed the model. Sometimes sidewall samples with enhanced content of metal demonstrated less value of conductivity as compared with other plastic self-extinguishing materials of sidewalls. XPS analysis showed that metals (Al, Cu, Zn, Mg) seen on the surface are in the oxidized form, as a result conductivity is not proportional to the metal content.

1. Introduction

High current arc accompanying electrical circuit breaking modifies insulating elements of circuit breakers that results in appearance of leakage currents and destroy cut outs. Investigation of conductivity of circuit breakers side walls exposed to arcs makes it possible to select materials of electrodes and insulators and thus to increase the efficiency and safety of circuit breakers.

The general purpose of our work is to investigate the reasons of the circuit breakers side wall conductivity changes as function of type of material used, parameters of arc exposure, temperature etc. As a rule, sidewalls manufactured from self-extinguishing plastics. After exploitation deposition of arc products on the walls takes place. This deposit consists of metal electrodes vapor as well as organics sputtered by arc from plastic walls. We investigated the composition and structure of deposits to understand the unusual behavior of sidewalls conductivity as function of temperature.

2. Experimental

The special thermostatic oven with the minimal thermal losses during sample heating and cooling in the range 20–170 °C was used for sidewalls samples electrical resistance R measurements. Distance between electrodes is ~ 1 cm; width is about 1 mm. Computer controlled $R(T)$ measurements with long term heating and cooling were carried out. Some materials did not reveal noticeable conductance but others (for example containing Zn) demonstrated surface resistance of order of MΩ before temperature measurements. The heating-cooling cycle continued for 12 hours. Fig. 1 shows that $R(T)$ is not monotonous function and demonstrates the clear maximum at T = 110–120 °C. The second feature of experimental results is the systematic increase of resistance with the time of measurements day after day.

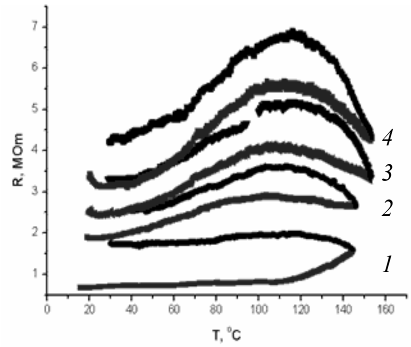

Fig. 1. Resistance of PA66.6 + 50%2ZnO – $3B_2O_3$ sidewall in 12-hour series of tests following one by one during 4 days (curves *1*–*4*). The beginning of measurements corresponds to the left part of the bottom curve

3. The Model of Conductivity of Samples

The theoretical model that had allowed to explain the experimentally measured features of sidewall conductivity dependence on temperature (Fig. 2) was proposed [3]. In brief the main bases of the proposed theoretical treatment are in what follows.

To explain the experimental data one can assume that conductivity of the deposit is provided with two mechanisms: metal-like conductivity through fractal metal clusters with whiskers that connect them with

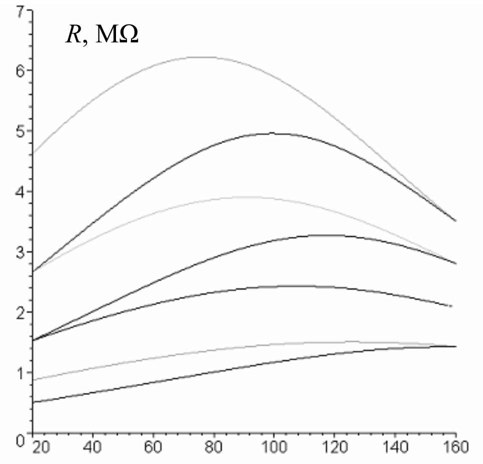

Fig. 2. Calculated dependence of deposit resistance versus temperature t

each other, and semi-conductor-like conductivity through porous graphite generated from plastic after exposure to circuit breakers arcs. Metal like conductivity should result in linear increase in $R(T)$ while the semiconductor-like conductivity should result in the decrease in R with temperature. We believe that the one-day heating-cooling cycle is a slow process, i.e., it is the equilibrium one. Annealing process can cause transformation of the fractal clusters into the island clusters. As a result, some whiskers providing metal conductivity can disappear. Also long-term annealing can lead to the additional oxidation of the fractal clusters. Apparently, both processes can lead to the decrease in the metal conductivity. Semi-conductor conductivity also can undergo the degradation. However, since the metal component of resistance is probably smaller, we believe that the increase in total resistance is mainly determined by the processes of degradation of a metal component of a film, rather than of a semi-conductor component.

The total resistance that follows from this model is determined as

$$R_n(t) = \frac{R_{10}(0)(1+\alpha t)f_n(t)}{1+\eta_0 \exp\left(\frac{1}{T_0}-\frac{1}{T}\right)(1+\alpha t)f_n(t)}.$$

The following designations are used in the equation: α is a usual temperature factor of resistance, $\eta_0 = \frac{R_{10}}{R_{20}} << 1$; $LR_{10} = 0.5$ MΩ, T – the absolute temperature, $T_0 = 300$ K, $f_n(t) = R_0(t)/R_0(0)$, ($R_0(t)$ is the temperature dependence of the natural resistance) represents degradation of R. Namely, $f_1(t) = \exp(\gamma t)$, $f_2(t) = \exp(2\gamma t_1 - \gamma t)$, $f_3(t) = \exp(2\gamma t_1 + \gamma t)$, etc. t_1 – temperature corresponding to the maximum value of R during the heating – cooling cycle. γ is the function of temperature rate during experiment and characteristic time of R evolution. Indexes at resistance designate various types of conductivity: 10 – corresponds to metal type, 20 – to semiconductor type of conductivity. n – number of a cycle, odd values of $n = 1, 3, 5, 7$ correspond to heating while even values of $n = 2, 4, 6, 8$ correspond to the subsequent cooling.

The results of the computer simulations made within this model (Fig. 2) describe all characteristic features of experimental results available.

4. XPS Results

Sidewall samples with enhanced content of metal demonstrated often less conductivity as compared with other plastic self-extinguishing materials of sidewalls.

The X-Ray photoelectron spectroscopy (XPS) was carried out using the XSAM-800 device. Energy resolution of the device is about 1 eV, residual gas pressure 10^{-9} Torr, irradiation of sample with MgK_α (energy of photons is 1253.6 eV), thickness of analyzed layer is 20–30 Å.

XPS analysis showed that samples of sidewall contain both metals belonging to primary plastic (Zn, Al) and to circuit breaker electrodes (Cu, Ag). Results presented in Fig. 3 show that, the all metals found in sample (Ag, Cu, Zn, Mg) are in the oxidized form.

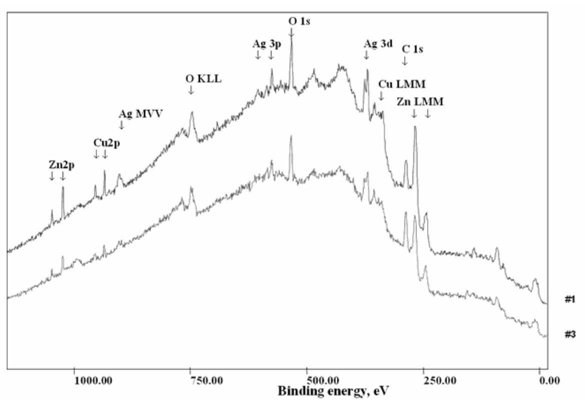

Fig. 3. XPS spectra representing two areas of the sample with different resistances

Relative quantities of different metals corresponding to XPS spectra shown in Fig. 3 (as compared with content of carbon) are presented in table 1. Area #1 has higher resistance then area #3 two orders of magnitude. But one can see from the data of Table 1 that percentage of metals with more high conductivity in area #1 is greater than for area #3 only two or three times.

Table 1. Relative content of different elements for XPS spectra shown in Fig. 3

	C1s	Ag3d	Cu2p	Zn2p	Al2p
#1	1	0.183036	0.154048	0.363881	1.48176
#3	1	0.098688	0.038087	0.220154	0.627413

This discrepancy can be explained by the fact that metals are in oxidized state that is confirmed by position of XPS peaks on the energy scale.

5. Microscopy

Samples also were analyzed by an optical microscope with the subsequent digital processing images. The visual acknowledgement of the proposed model of conductivity had been obtained: namely, the presence of conducting clusters of metals connected by whiskers on a surface (Fig. 4). Dimensions of metal clusters are of order of several microns, traversal width of "whiskers" is less the 1 micron, but length is of order of 10 microns.

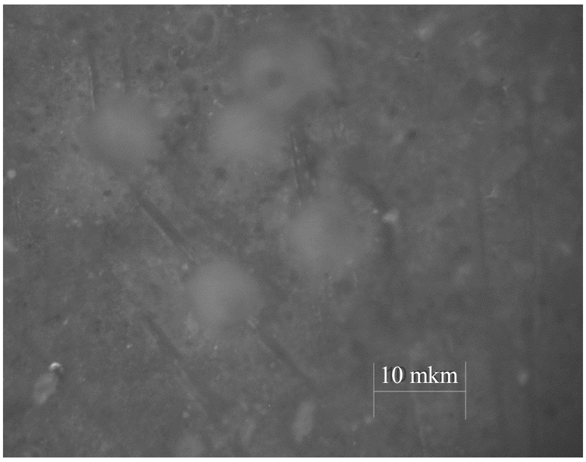

Fig. 4. Metal cluster group connected with whiskers

6. Conclusion

Experiments on dependence of resistance of a sidewall layer of circuit breakers on temperature and time have shown that non-monotonic change of resistance with temperature change takes place with a maximum and the increase of resistance in series of subsequent heating cooling cycles. The model takes into account combination of metal type (with linear dependence of resistance R on temperature T) and semi-conductor type (with falling of $R(T)$) and degradation of conductivity with time. Possible reason of such behavior of R with time and temperature can be caused by destruction at heating and also in time of thin metal whiskers connecting metal grains on the surface. This proposal has been confirmed by the direct microscopic observations. Different materials used as sidewalls of circuit breakers and exposed to arcing demonstrated different primary conductivity irrespective to the position in circuit breaker. XPS diagnostics of a surface has shown that all elements (Al, Cu, Zn, Mg, etc.) presented in the deposit are only in the oxidized state, that defines similar dependence $R(T)$.

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