Development of Contact Material Solutions for Low-Voltage Circuit Breaker Applications (1)

Timo Mützel, Peter Braumann, Ralf Niederreuther
Umicore AG & Co. KG
Business Line Contact Materials, Applied Technology
63457 Hanau-Wolfgang, Germany
timo.muetzel@eu.umicore.com

***Abstract*—The focus of the studies is on the influence of contact material production parameters, and the contact material - breaker interaction of material combinations used for low voltage protection devices.**

The influence of the magnetic blast field and the material composition on erosion behavior and contact resistance of AgW materials will be scrutinized by model-switch tests. Especially the mass loss during break operation is heavily influenced by the applied magnetic flux density. Furthermore the switching performance of AgC materials with different manufacturing parameters and fiber orientation will be compared. The improved erosion rate of optimized AgWCC materials in comparison to AgC during electrical lifetime test will also be pointed out.

The paper represents a guideline for material selection and problem solving during protection device design by comparing the varying contact material behavior under different types of loads.

contact material; circuit breaker; silver graphite; silver tungsten; silver refractory metal

I. Introduction

The development of electrical protection devices like circuit breakers is driven by device miniaturization and cost efficiency. Protection devices like circuit breakers have to fulfill various requirements. Contact materials for this kind of application should provide excellent anti-welding behavior, low contact resistance, low erosion rates and good arc root mobility. Solutions applying different or identical contact materials for both moveable and fixed contact are known. Examples of possible material combinations, manufacturing technologies and general differences in the switching behavior are shown in [1].

Contact materials made of silver refractory metals (e.g. AgW, AgWC, AgMo) are often used as arcing contacts due to their resistance against arc erosion. [2]

Silver graphite (AgC) is also often applied as contact material for protection devices, because of its excellent resistance against welding and its low and stable contact resistance. Typically silver graphite variants with graphite contents from 2 to 6 weight percent (wt.-%) are used. On the other hand AgC shows relatively high erosion rates because of the low thermal stability of carbon in air and the carbon stabilizing the electric arc, resulting in a bad arc movement. With increasing graphite content the resistance against welding increases, but also erosion rises. Therefore a suitable compromise has to be found for the breaker solution as already pronounced in [3]. This paper shows basic principles to find this solution between breaker design and contact material.

II. Influences on the Switching Behavior of Silver-Tungsten Materials

Silver-tungsten AgW is widely used as arcing contact material in high current applications (e.g. circuit breakers) due to its low erosion rate. Different AgW probes with 50 wt.-% and 65 wt.-% tungsten content have been manufactured by

- powder blending
- pressing
- sintering and
- infiltration.

Break-only model switch tests have been performed to study the influence of the tungsten content on the switching behavior under overload conditions. The applied model switch has already been described in [4, 5]. The contacts are opened synchronously to the voltage phase angle (at natural current zero) and the current flows for one half-cycle until next current zero. Due to some mechanical reaction times the duration of a half cycle is 8.7 ms. The arc can be forced to commutate onto copper arc-runners by a self-induced magnetic field. The range of magnetic fields can be chosen in a typical range for switching devices. Two setups (magnetic flux density B of 0 mT/kA and 15 mT/kA) have been chosen for the tests to analyze the influence of the magnetic breaker design on the switching behavior of AgW contact materials. The different compositions of AgW have been applied to the moveable and fixed contact for the switching test. After current zero the contacts are re-closed without current flow for contact resistance measurement. The voltage drop across the contacts is measured at a 10 A DC current. Thereafter the supply voltage is applied and the controller starts to open the contacts again. The direction of the current flow is alternated at every switching cycle. The detailed electrical parameters chosen for the break-only model switch tests are summarized in Table I.

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TABLE I. TEST PARAMETERS – BREAK-ONLY MODEL SWITCH

Parameter	Value
voltage *U*	230 V
current (peak value) *î*	1,300 A
power factor *cosφ*	0.35±0.05
magnetic field *B*	0 or 15 mT/kA
opening velocity *v*	0.4 m/s
number of operations *n*	500
contact diameter Ø	8.0 mm

The resulting dwell times of the electric arc for different tungsten contents and magnetic flux densities are shown in Fig. 1. The dwell time of materials tested was defined by the time period from contacts opening – detected by the initial anode-cathode voltage drop – until a voltage drop of 60 V across the contacts is reached. This voltage drop is the typical value for the commutation of the breaking arc onto the arc runners taking place in the applied model switch.

The estimation of energy at break W_{break}, which is transferred by the arc root into the contact material, for the single-breaking contact system of the model switch, is carried out by integrating the product of the minimum arc voltage U_{min} and the current from contacts opening until 60 V (equals dwell time) are reached:

$$W_{break} = U_{min} \int_{t_1}^{t_{60V}} i(t)\, dt \qquad (1)$$

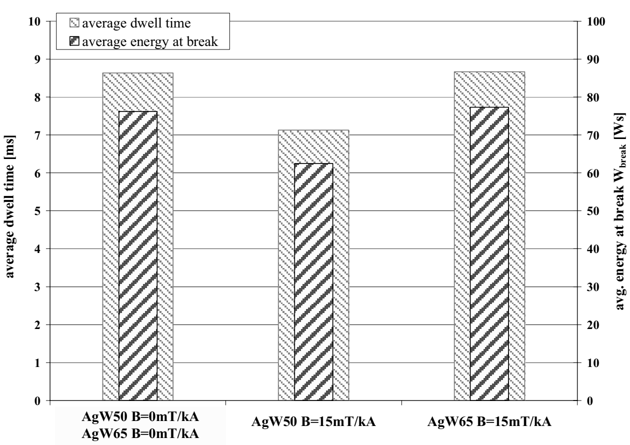

Figure 1. Average dwell times and energies at break

Only for AgW50 the arc could be effectively driven off the contact material by a flux density of 15 mT/kA resulting in average dwell times of 7.1 ms after the edge of the tip was softened by erosion and commutation onto arc runner became easier. For AgW65 it was not possible to move the electric arc off the contact tip by the applied magnetic field. Of course 15 mT/kA is a rather small value for a good circuit breaker design, but the tests were carried out to show the differences between the contact materials. Therefore a value on the edge between arc commutation and no arc commutation has been chosen.

Due to arc movement and therefore shorter dwell times the energy level of the AgW50 material at a flux density of 15 mT/kA is lower than in all other experiments (approx. 62 Ws in comparison to 77 Ws). As already shown in [6], contact materials providing a higher silver content improve the arc movement.

The total mass loss or erosion of the contacts is determined by weighing the contacts before and after switching test. Figure 2 shows the total mass loss of the different variants.

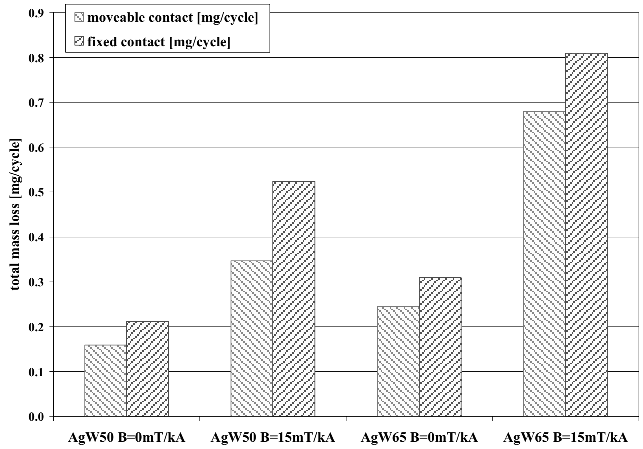

Figure 2. Total mass loss

If a magnetic field is applied during the breaking event higher contact erosion can be observed. Furthermore the mass loss of the AgW65 material is higher than that of the AgW50 material. This total mass loss has to be divided by the energy at break for comparing the materials under consideration of the differences in arc root mobility. The resulting specific erosion rates are shown in Fig. 3.

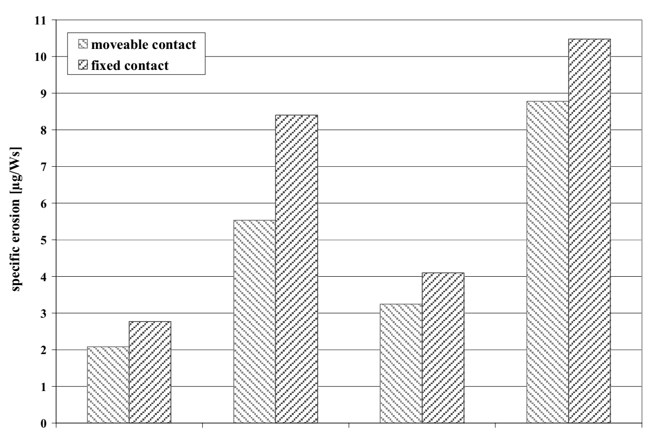

Figure 3. Specific erosion

Higher specific erosion rates can be observed if a magnetic field is applied, even at experiments without arc commutation. This happens due to an elongated/bellied arc column at those experiments, so that evaporated contact material cannot re-condense on the contact tip after the arc has extinguished. Furthermore, evaporated ionized metal is also blown away by the magnetic field.

Higher specific erosion rates for AgW65 material in comparison to AgW50 have also been observed. The metallographic property of contiguity of the refractory phase seems to correlate with the erosion rate, thus as the brittle paths through the material become more continuous the specific erosion increases. That means increasing the refractory content increases contiguity and therefore erosion [7].

The average value and the 99% quantile of the contact resistances, which were measured between each switching event, are shown in Fig. 4.

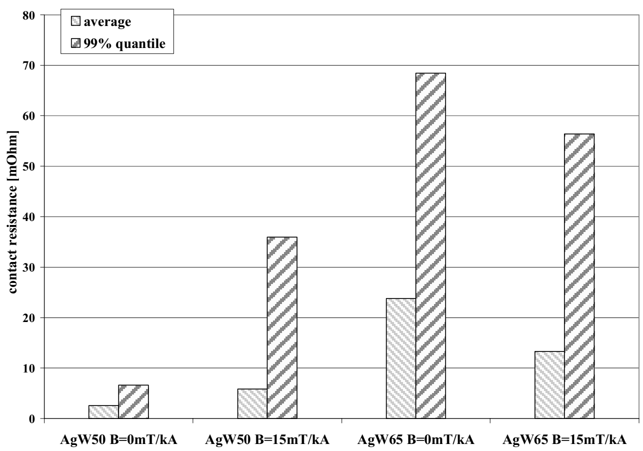

Figure 4. Contact resistance

AgW65 shows a higher contact resistance than AgW50 in all experiments. At AgW50 the contact resistance increases by applying a magnetic field, while it decreases at AgW65.

Due to the intense formation of tungsten oxide and silver tungstate on the surface a higher contact resistance can be found for AgW65 in comparison to AgW50. The evaluation of the contact resistance during the switching cycles shows that these surface layers are built step by step and rise during several break operations. Furthermore a strong dependence of the contact resistance on switching current of AgW materials is shown in [8]. At rated current the contact surface is covered with semi-conducting layers, while at high currents the surface is free of such layers as a result of erosion. Applying a magnetic field to the AgW50 material leads to higher contact resistances, because the arc root melts and evaporates the silver in the contact area and the magnetic field blows it away; a tungsten rich area remains at the contact spots. Figure 5 shows such a surface area in a cross section of the contact tip after switching test. The light colored phase represents silver, the grey colored phase tungsten and the black areas are voids. The silver depletion and the appearance of voids are significant in the heat-affected arcing zone.

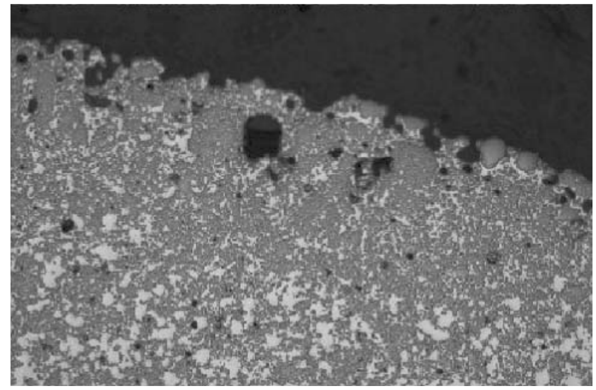

Figure 5. Surface of AgW50 after model switch test (B = 15 mT/kA). Magnification 100:1

At AgW65 the massive erosion of the brittle tungsten matrix cleans the surface during the test and provides a lower contact resistance compared to the experiments without magnetic field. Without magnetic field it takes a higher number of switching cycles to clean the surface by erosion due to the lower total mass loss than at break operations with magnetic field applied (Fig. 6). Therefore, the contact resistance drops down to a lower limit of a few milliohms more often during the experiments with magnetic field.

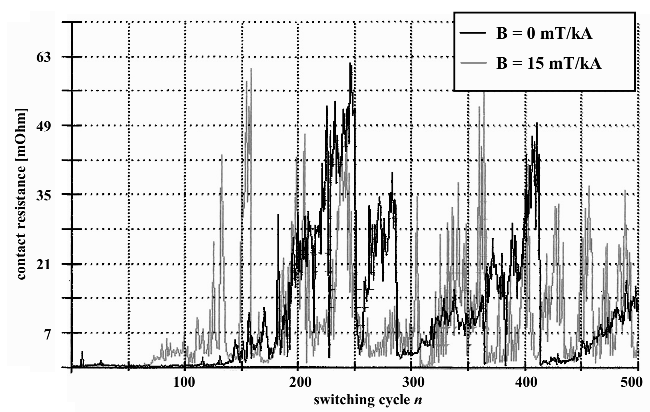

Figure 6. Contact resistance evaluation of AgW65 at different magnetic flux densities

III. INFLUENCE OF PRODUCTION TECHNOLOGY ON SILVER-GRAPHITE MATERIALS

AgC is often used as a solution for the fixed contact in combination with AgW, AgWC, AgNi, Ag/SnO_2 or Cu as moveable contact in protection devices. Therefore the influence of the production technology on the switching behavior of AgC has been studied as a support for choosing the ideal combination for different device solutions. The AgC samples were produced by

- powder blending and extrusion for oriented graphite particles
- and powder blending, compaction and sintering for sintered tips.

Ag/SnO_2 on moveable and AgC on fixed contact is a typical combination applied in miniature circuit breakers according to IEC standards. The following break-only model switch tests were performed with Ag/SnO_2 88/12 SPW4 as moveable contact and different types of AgC5 as fixed contact. The orientation of the AgC with parallel microstructure was normal to the magnetic field, but random to the direction of arc movement. Investigations [5] have shown no significant influence of this orientation on the results achieved by the model switch. The detailed test parameters are shown in Table II.

TABLE II. TEST PARAMETERS – BREAK-ONLY MODEL SWITCH

Parameter	Value
voltage U	230 V
current (peak value) $\hat{\imath}$	1,300 A
power factor $cos\varphi$	0.35±0.05
magnetic field B	30 mT/kA
opening velocity v	0.4 m/s
number of operations n	150
contact diameter Ø	8.0 mm

A magnetic flux density of 30 mT/kA has been chosen to ensure a stable, constant and similar arc movement for all tested AgC5 variants. This behavior can be seen in almost constant dwell times (Fig. 7) for all experiments, after a certain inrush effect – represented by the 90% quantile – has taken place. Therefore a comparable energy at break ($W_{break} \approx 60$ Ws) has been achieved during the tests.

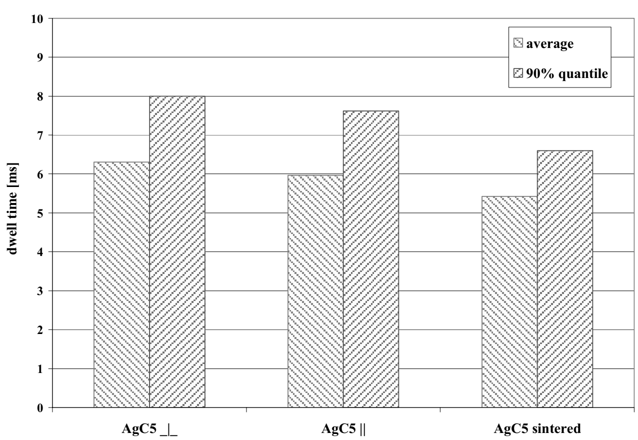

Figure 7. Dwell time

The average dwell time for all experiments is approx. 5.7 ms. This means that a stable arc movement was achieved for this material combination applying a magnetic field of 30 mT/kA. The higher 90% quantile of the dwell time is a result of an inrush effect. During the first switching cycles no arc commutation takes place, because the arc root stops at the sharp edge of the contact tip. This edge is softened by erosion after some break operations and the arc can easily commutate onto the arc runners. The observed total mass loss of the different AgC5 fixed contacts is shown in Fig. 8.

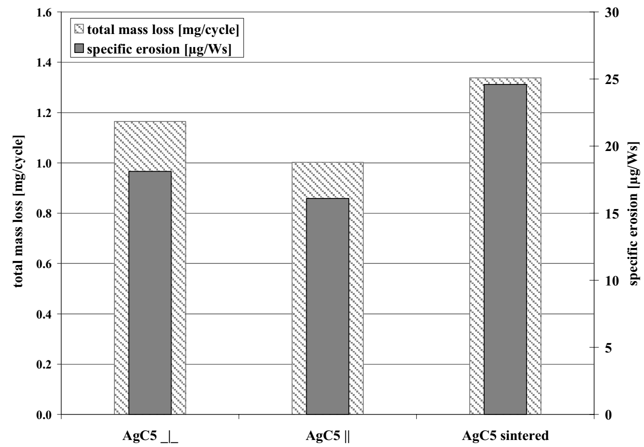

Figure 8. Total mass loss and specific erosion

Lowest erosion was observed for materials with graphite particles parallel to the contact surface in comparison to perpendicular. The differences can be explained by the variations in the heat conduction of the two material structures and the deep decarbonized craters on the switching surface (Fig. 9, top) of AgC _|_ contact materials.

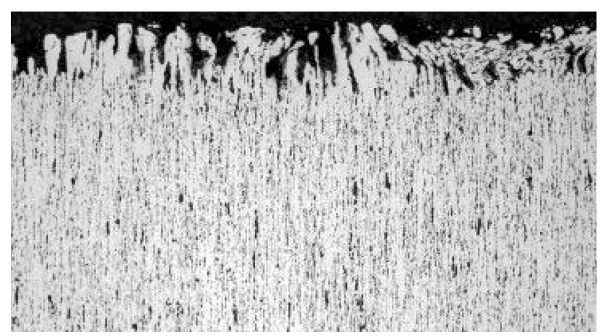

Figure 9. Cross section of a AgC5 _|_ switching surface after model switch test. Magnification 100:1

Intermediate erosion rates were found in [9] for materials where the graphite alignments show an angle of 45° to the contact surface. These results confirm the dependence of erosion being a function of graphite orientation as shown in [10, 11]. Furthermore the tests in [9] showed a reduction in erosion for increasing elongation ratios of the extruded material. The higher erosion rate of the sintered AgC5 material can be explained by the weaker silver matrix with more entrapped gas of this process. The higher erosion also accounts the shorter inrush effect of the dwell times in Fig. 7. This effect can be eliminated by looking at the specific erosion of the materials (Fig. 8). Here the difference between extruded and sintered AgC materials is even more significant.

In addition, rising erosion rates with increasing graphite content have been shown in [10]. The influence of graphite particle size and sintered density on the switching performance of sintered AgC5 contacts was studied in [12]. Silver-graphite materials with larger graphite particles showed lower erosion rates as a result of a stronger silver matrix by greater particle spacing.

Ag/WC/C was developed for combining the good resistance against welding of AgC contact materials with the low erosion rates of silver refractory metal contacts. Electrical lifetime tests in accordance to IEC [13] applying three different types of Ag/WC/C 70/27/3 materials to the fixed contact of standard circuit breaker have been performed. AgW50 was used as moveable contact. The detailed test parameters are summarized in Table III.

TABLE III. TEST PARAMETERS – ELECTRICAL LIFETIME TEST

Parameter	Value
voltage U	690 V
make/break current $I_{make/break}$	160 A
power factor $cos\varphi$	0.9
switching frequency	120 1/h

The tested Ag/WC/C 70/27/3 materials have been produced by powder blending, pressing, sintering and repressing. Type I is a material from the Asian market and type II a material from the American market. Type III is an improved material with optimized production parameters (grain sizes, pressures, and sintering temperature). Figure 10 shows cross sections of the type I and type III material. The white phase represents the silver, the black is carbon and the grey is tungsten-carbide. The main difference in the material structure can be seen in the coarser carbon phase of the type III material.

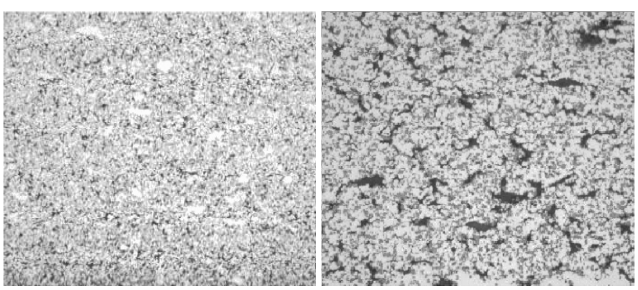

Figure 10. Cross sections of type I (left) and type III (right) AgWCC. Magnification 100:1

The calculation of energy at break during the lifetime tests for the single-breaking circuit breaker is carried out in accordance to Eq. 1. The mass loss Δm is determined by weighing the fixed contacts several times during the test. From these values the erosion in all three phases can be plotted (Fig. 11). The slope of the linear regression over all three phases represents the erosion rate of the material. The erosion on make can be neglected for this test. Therefore the regression through zero is valid.

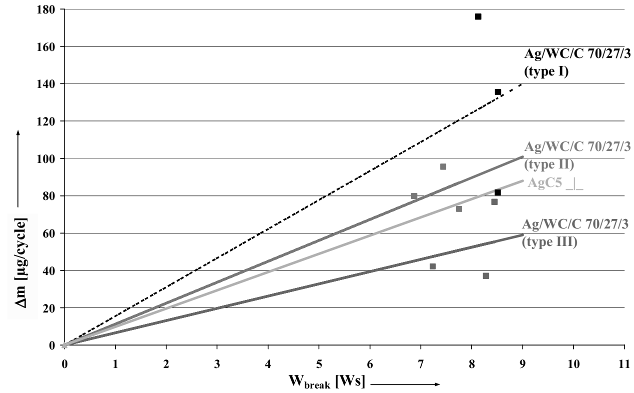

Figure 11. Erosion rates of AgWCC and AgC materials in circuit breaker application

The type I material shows a wide range of dispersion in the loss of material, even though similar energies have been converted in all three phases. This is a result of a manual and instable production process. This range is smaller for the type II material. Furthermore, the average erosion rate (regression) is lower. Unfortunately, the erosion rates of both materials are higher than that of a standard AgC5. Only the type III material provides lower erosion rates than AgC5 and can improve the electrical lifetime or save precious metal by possibly smaller tip size.

Similar temperature rise test results for all tested material combinations have been achieved due to wiping action, high contact forces, and large heat sinks of the used circuit-breaker.

IV. CONCLUSIONS

The focus of the presented experimental studies was on the influence of contact material composition and production parameters on the switching behavior, and on the interaction of contact material and low voltage protection device (e.g. magnetic fields).

A significant influence of the magnetic field and the material composition on the erosion behavior as well as on the contact resistance of AgW materials was shown by break-only model switch tests at 1,300 A. The formation of tungsten oxide and silver tungstate on the surface leads to higher contact resistances for increasing tungsten contents. The evaluation of the contact resistance during the switching cycles shows that these surface layers are built step by step and rise during several break operations. Especially the material erosion is heavily influenced by the applied magnetic flux density. Magnetic fields can easily double the mass loss, without any changes in the dwell time and therefore energy at break. Consequently a good compromise for the magnetic field has to be found in the breaker design. The magnetic field can reduce the total mass loss by moving the arc root away from the contact material and therefore reducing the converted energy. But, if it is too high it will have a severe impact on the material erosion.

Differences in the switching performance of AgC materials with different manufacturing parameters and fiber orientation have also been shown by break-only tests at 1,300 A. Lowest erosion was observed for materials with graphite particles parallel to the contact surface under these conditions. Sintered AgC material showed the highest erosion rate, which can be explained by the weaker silver matrix with more entrapped gas. Of course a suitable compromise has to be found for each breaker design.

Standard Ag/WC/C 70/27/3 contact materials still showed erosion rates similar to AgC5 during electrical circuit breaker lifetime tests. Only Ag/WC/C with optimized production parameters (especially grain sizes, pressures and sintering temperatures) provides lower erosion rates than AgC and can improve the electrical lifetime or save precious metal by a possible smaller tip size.

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Timo Mützel received the Dipl.-Ing. (2003) and the Dr.-Ing. (2008) in Electrical Engineering and Information Technology from TU Ilmenau, Germany. From 2003 to 2007 he was with the department of Electrical Apparatus and Switchgear at TU Ilmenau. His research areas included switchgear technologies, numerical simulations and transients in power systems. In 2008 he joined Umicore AG & Co. KG, Hanau, as Manager Applied Technology in the business line Contact Materials. He is responsible as well for technical customer support as for assistance on contact material development regarding switching phenomena. He is a recipient of the 2003 VDE Adam-Herbert-Prize.

Peter Braumann received his Dipl.-Ing. degree in 1973 in Electrical Engineering from the Technical University Braunschweig, Germany. From 1973 to 1979 he did research at the Institut für Hochspannungstechnik at the same university. In 1981 he received his Dr.-Ing degree. From 1979 to 1982 he was associated with the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany. In 1982 he joined Umicore, Hanau, Germany and is responsible for contact testing and applied technology. In 2009 he received the Albert-Keil-Preis for his merits in the field of electrical contacts.

Ralf Niederreuther received the Dipl.-Ing. degree in Electrical Engineering from the Technical University Darmstadt, Germany, in 2006. Since 2006 he is with Umicore AG & Co. KG as Manager Applied Technology in the business line Contact Materials and primarily engaged in experimental investigations on contact materials.