Contact Material Combinations for High Performance Switching Devices

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***Abstract*— Latest developments in the fields of regenerative energies, industrial automation and automotive application generate new technical requirements for switching devices and contact materials.**

Rising energy densities in such devices were simulated by contactor endurance tests under heavy duty load. The results show a strong exponential relationship between arcing energy at break and contact material erosion; this effect has to be considered carefully in device design. Opportunities for precious metal reduction and/or enhanced switching capacity were found for Ag-SnO_2 materials with increased total metal oxide content.

The dynamic sticking behavior at make operation is a second important characteristic of electrical contacts. Especially the application of asymmetric material combinations for cost saving issues – e.g. replacing one side of a symmetric silver metal oxide combination by silver nickel – can lead to unexpected device failure. Appropriate model switch tests and corresponding metallography can demonstrate that behavior.

contact material; contactor; silver tin oxide; silver zinc oxide; silver nickel; precious metal saving

I. Introduction

Rising demands for electrical energy, megatrends like "renewable energies" and "electric vehicle" characterize the field of contacts for electrical power engineering. Electrical energy consumption is predicted to rise by 49% in the years 2007 to 2035. The share of electrical energy carriers is about to grow by 87% within the same time frame [1]. This increase and the decentralization of power generation by renewables will require complex grid structures with longer transmission distances and the development of smart grids.

In parallel general technological trends within electro-mechanical device design are ongoing. Miniaturization leads to increased energy densities within the switching devices. Furthermore, energy consumption is reduced by decreasing contact forces electronically in on position of contactors. The electronic coil control can optimize bouncing behavior of the device, too [2]. Furthermore, rising precious metal prices are forcing device manufacturers to precious metal reduction (e.g. contact material change, contact tip size reduction, base metal layers).

Additionally, within the emerging application fields "renewable energies" and "electric vehicle" switching of high DC ratings with voltages up to 1500 V (e.g. photovoltaic, battery main switch) is mandatory.

Together, these developments create further technical requirements for electromechanical switching devices and contact material regarding all three basic aspects – weld break forces, contact resistance, and material erosion. Switching of direct currents additionally requires high arc root mobility and low tendency to contact material migration. The paper will provide experimental results and approaches as a basis for contact material selection during the development phase of high performance switching devices.

Electromechanical switches like contactors are used for switching motor loads. Typically AgNi contact materials are applied for contactors with small switching capacity. For higher rated contactors silver metal oxide materials – especially Ag-SnO_2 and Ag-CdO – are widely used.

All contact materials under test have been produced by

- powder blending,
- pressing,
- sintering,
- and extrusion.

The following material compositions are given in mass percent:

- Ag-SnO_2 88-12 SPW7: additives Bi_2O_3, WO_3
- Ag-SnO_2 86-14 PMT3: additives Bi_2O_3, CuO
- Ag-ZnO 92-8 SP (w/o additives)
- AgNi 90-10

II. Contact Material Erosion and Contact Resistance

Contact material erosion and contact resistance are the main parameters to benchmark contact materials for high performance switching devices within this section. Test parameters have been selected to simulate possible stresses during the application of such devices.

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In a first step electrical endurance tests have been performed applying a standard 132 kW contactor. Detailed test conditions are summarized in Table I.

TABLE I. TEST PARAMETERS 132 KW CONTACTOR

Parameter	Value
voltage U	400 V
current I	1000 A
power factor $cos\varphi$	1
switching frequency	250 1/h

Figure 1 shows the material loss Δm_n over the average energy at break W_{break} per operation. According to [3] the energy at break of a contactor with two serial contacts is calculated by multiplying two times the anode-cathode voltage drop U_{AC} by the current integral. The phase current is integrated from contact opening t_1 until arcing voltage reaches 100 V (estimated commutation voltage from various experiments):

$$W_{break} = 2 \cdot U_{AC} \int_{t_1}^{t_{100V}} i(t)\, dt \qquad (1)$$

After the electric arc has commutated from the contact tips onto arc runners or into splitter plates the arc voltage instantaneously increases above the threshold value of 100 V.

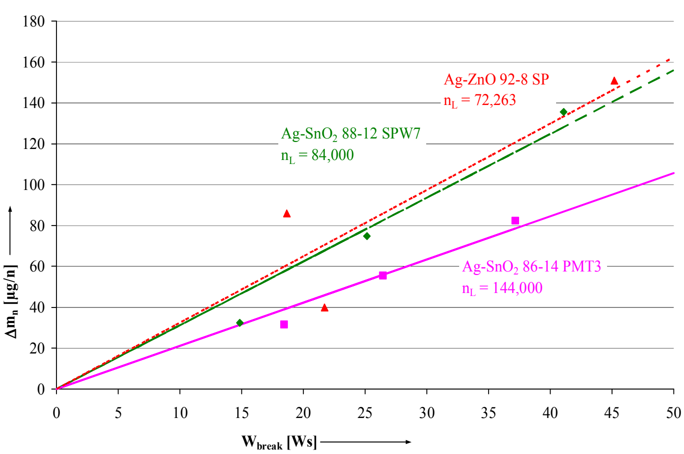

Figure 1. Material loss over energy at break for different silver-metal oxide contact materials

The average mass loss per switching cycle Δm_n in each phase is determined by weighing the contacts. The mass difference before and after test is divided by the number of switching operations. Each point in Figure 1 is representing the mass loss of a single contactor phase. Afterwards, linear regression through origin, neglecting the influence of contact make as arcing energies are significantly lower, is made. The gradient m_a describes the erosion behavior of the contact material loaded with a certain amount of arcing energy and therefore the performance of the contact material regarding erosion by arcing.

$$m_a = \Delta m_n / W_{break} \qquad (2)$$

Figure 1 shows similar contact erosion for Ag-ZnO 92-8 SP and the standard material in this application Ag-SnO_2 88-12 SPW7, which can be derived from the two comparable linear slopes m_a – representing a comparable material performance regarding break arc erosion under the tested load conditions. The lower electrical lifetime, given by the lower total number of operations n_L of the Ag-ZnO material, is a result of the higher energy at break W_{break} within the highest loaded phase. This difference in arcing load is caused by mechanical tolerances within the contactors and differences in synchronism of the actuating system with the driving voltage at contact break, as explained in [3]. Therefore, the number of achieved operations is not sufficient to benchmark contact materials in an electrical endurance test.

Ag-SnO_2 86-14 PMT3 shows lower material loss (arcing erosion) compared to the two other materials under test by more than 30%, which is emphasized by the lower gradient of the regression line. Finally, a significantly higher electrical lifetime n_L is reached, partially supported by lowest energies at break within the highest loaded phase on this specific contactor.

Furthermore, the temperature rise behavior of the different contact materials was studied. Therefore, temperature rise tests at rated current were performed several times during the electrical endurance test (24 hour cycling test incl. dry switching every 1 hour; maximum temperature value of the three movable contacts before dry switching is stored). The quantiles of Ag-SnO_2 88-12 SPW7 and Ag-ZnO 92-8 measured at the contact bridges within the device are on a comparable level (Fig. 2). Temperature values for Ag-SnO_2 86-14 PMT3 are approximately 5 K higher, but with a lower variance. This specific behavior of contact material variant PMT3 was seen in several other experiments, too.

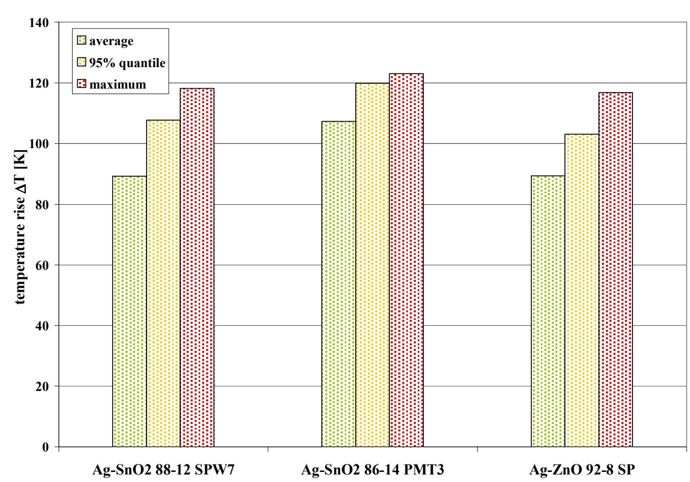

Figure 2. Temperature rise test results on movable contacts

Linear regression of breaking arc erosion phenomena as shown in Fig. 1 is suitable only for small range of break arc energies, typically one device type at one defined load. An exponential dependence of material erosion and arcing current and arcing work respectively was already shown in [4]. In the following the erosion behavior of two Ag-SnO_2 variants (88-12 SPW7 and 86-14 PMT3) will be studied for a larger range of break arc energies. Therefore, additional experiments including contactors of various power ratings have been performed. Four times rated AC-3 current at make and break operation at power factor *cosφ* = 1 has been chosen as electrical load for contactor endurance tests. Figure 3 shows the resulting contact material erosion for Ag-SnO_2 88-12 SPW7.

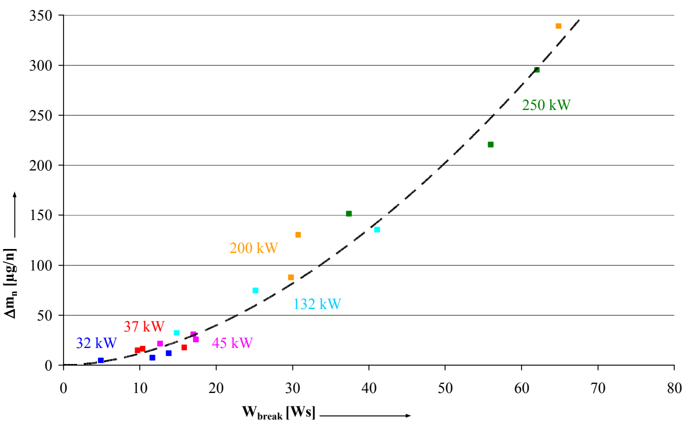

Figure 3. Material loss over energy at break of Ag-SnO_2 88-12 SPW7 for different contactor ratings

The following correlation between material loss and arcing energy at break operation can be derived for Ag-SnO_2 88-12 SPW7 by least squares method*:

$$\Delta m_n = 0.194 \cdot W_{break}{}^{1.78} \tag{3}$$

The resulting erosion values for Ag-SnO_2 86-14 PMT3 are plotted in Fig. 4.

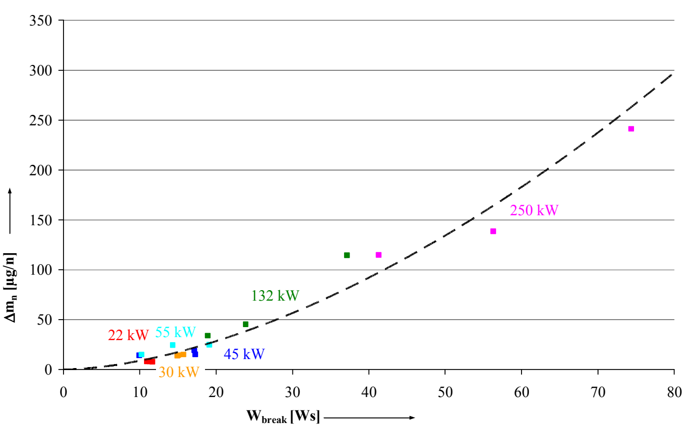

Figure 4. Material loss over energy at break of Ag-SnO_2 86-14 PMT3 for different contactor ratings

* Of course least squares method should mathematically not be applied on the data sets as they are taken from statistically independent tests (e.g. boundary conditions for the different contactor ratings), but it can be a simple demonstration tool for comparing two materials under the defined boundary conditions.

The regression for Ag-SnO_2 86-14 PMT3 can be calculated as:

$$\Delta m_n = 0.129 \cdot W_{break}{}^{1.78} \tag{4}$$

The erosion behavior of the two materials can be compared by a division of Eq. 3 and Eq. 4:

$$\frac{0.129\, W_{break}^{1.78}}{0.194\, W_{break}^{1.78}} = 0.665 \tag{5}$$

This relationship expresses a reduction of contact material erosion under heavy duty load of approx. 33.5% by applying Ag-SnO_2 86-14 PMT3 instead of Ag-SnO_2 88-12 SPW7 (compare results of Fig. 1). Further experiments have proven that this effect is driven by the different total metal oxide content of the contact materials and not by the used additives. Silver tin oxide materials with increased total metal oxide content – as shown on the variant 86-14 PMT3 – offer potential for precious metal saving by their lower silver content and especially by possibilities for contact tip volume reduction as result of lower material erosion.

As already mentioned above, one will find different sizes of contact tips applied for the different tested contactor sizes. Furthermore, the device design will change from small rated powers w/o arc runners and splitter plates to higher rated powers. In addition kinematics like opening velocity or the magnetic fields are different. Figure 5 and Fig. 6 are showing material loss over area related energy at break of both Ag-SnO_2 variants under test to eliminate the influence of the differences in contact area related energy at break (W_{break}/A) within the various contactor ratings.

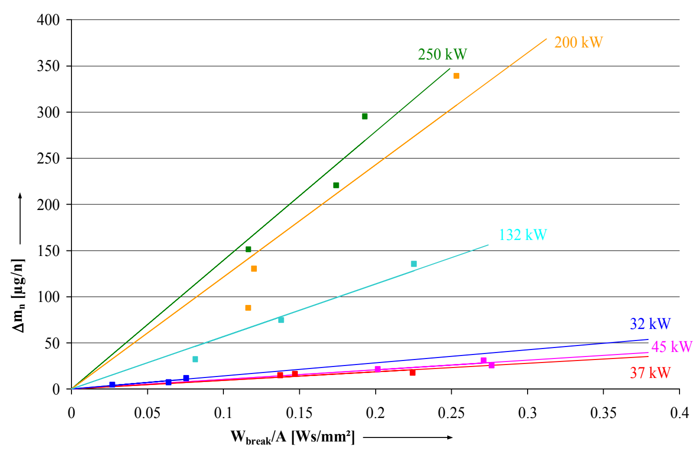

Figure 5. Material loss Δm_n over area related energy at break W_{break}/A of Ag-SnO_2 88-12 SPW7

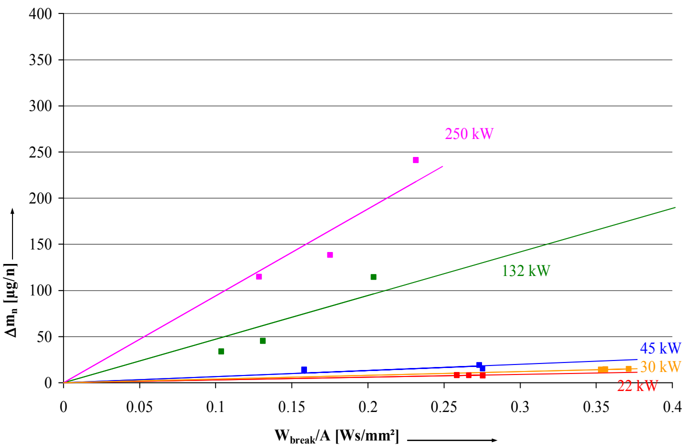

Figure 6. Material loss Δm_n over area related energy at break W_{break}/A of $Ag\text{-}SnO_2$ 86-14 PMT3

A linear relation between mass loss and area related break arc energy was estimated for the different contactor ratings. A comparable slope can be found for small and medium rated contactors (up to 45 kW). Contact loadings for higher rated contactors are lower by a factor of approx. two. Mass losses and slopes of the linear regression are on a much higher level for higher power ratings. This increase is caused by the differences in device design for the diverse rated powers. Contactors of higher rated powers are supporting arc commutation by magnetic arc blowing. The magnetic fields are realized by self-induced current loops. Thus, commutation times and consequently energy conversion in the device at contact break are reduced. The significant increase the contact erosion under the influence of increased magnetic fields was already shown in [5] for AgW materials. Rising contact erosion with increasing magnetic field strength at identical arc root energy stressing the contact tip was shown in [4] as well.

III. Weld Break Forces

Dynamic welding of contacts during make bounce is – in addition to the above studied erosion phenomena – another key aspect for contact material selection. The application of energy efficient electrical motors increases the required make capacity of electromechanical contactors. Transient inrush currents of 15 to 20 times rated current are reported [6] for direct switching of energy efficient machines.

The dynamic welding behavior of different contact material combinations for contactor application can only be studied under well defined and stable boundary (bouncing) conditions. Make-only model switch tests have been performed, realizing this stable mechanical set-up. A detailed description of the hardware set-up and the performed test can be found in [7]. Electrical and mechanical parameters applied on the test are summarized in Table II. The contacts are closed synchronous to the voltage phase angle (at natural current zero) and therefore stable bounce arc energy W_{make} can be realized. The tests are done with an alternating polarity of the electrodes to avoid influences by material migration.

TABLE II. Test Parameters Make-Only Model Switch

Parameter	Value
voltage U	230 V
current (peak value) $\hat{\imath}$	700 A
power factor $cos\varphi$	0.35
closing velocity v	1 m/s
bouncing time t_{bounce}	1 ms
avg. bounce arc energy W_{make}	3.5 Ws
contact force F	3.5 N
number of operations n	300
contact diameter D	4.0 mm

Resulting weld break forces of symmetrical and unsymmetrical material combinations are plotted in Fig. 7. 99.5% weld break force quantiles and their min./max. deviations of at least two independent tests are presented.

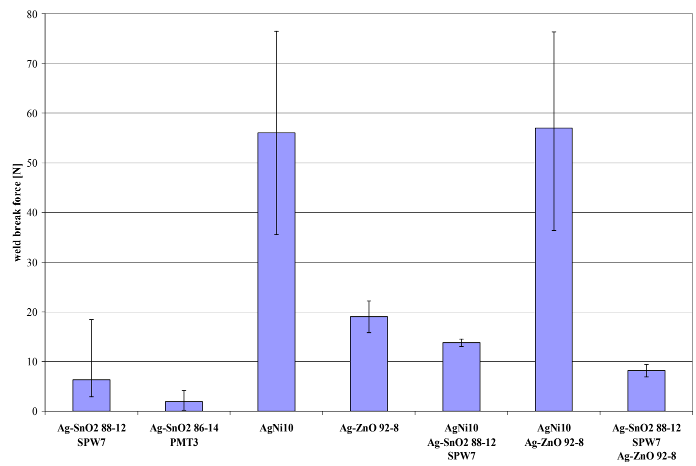

Figure 7. Weld break forces of typical contactor contact materials and combinations (99.5% quantile)

Lowest weld break forces can be observed for the symmetrical $Ag\text{-}SnO_2$ variants. These forces can be influenced as well by the total metal oxide content as by the chosen additives. Within the tested power range the measured weld break forces of $Ag\text{-}SnO_2$ 86-14 PMT3 are significantly lower than those of $Ag\text{-}SnO_2$ 88-12 SPW7 due to the 2% higher total metal oxide content. Considerably higher forces were needed to break the welds of the silver metal oxide Ag-ZnO 92-8. The volume content of metal oxides has to be considered carefully, as it is a main parameter influencing weld break forces and contact material erosion by arcing. Volume contents of tested silver metal oxide types are summarized in Table III. This explains the highest weld break forces within the symmetrical silver metal oxide combinations to be found for Ag-ZnO 92-8. AgNi10 is building the strongest welds amongst symmetrical material combinations as expected. These high weld break forces are the result of pure intermetallic connections without brittle phases within the contact surface structure.

TABLE III. METAL OXIDE VOLUME CONTENTS

Contact Material	Metal Oxide Content [vol.-%]
Ag-SnO_2 88-12	17.1
Ag-SnO_2 86-14	19.7
Ag-ZnO 92-8	14.5

The following results, which were confirmed by additional device tests, have been found for the unsymmetrical combination of silver metal oxide and silver nickel. The 99.5% weld break force quantile for the combination of a movable AgNi10 and a stationary Ag-SnO_2 88-12 SPW7 can be found in between the two symmetrical combinations. In contrary weld break forces on the level of a symmetrical AgNi10 combination are achieved when the stationary contact is replaced by Ag-ZnO 92-8. The weld break forces of the combination of Ag-SnO_2 and Ag-ZnO are slightly higher but close to the symmetric application of Ag-SnO_2.

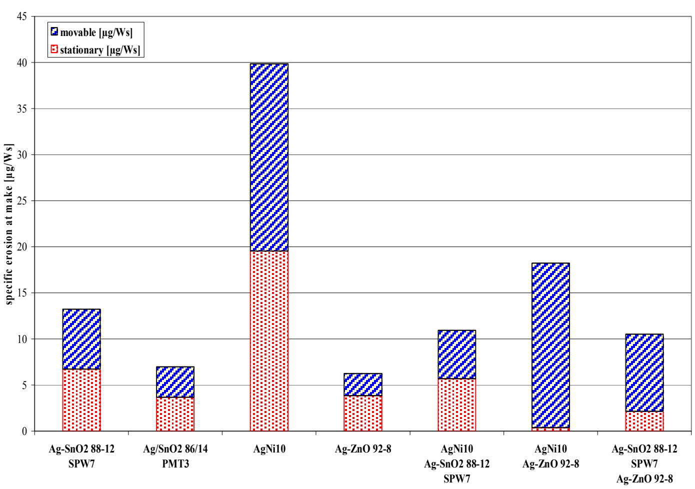

Figure 8. Specific material loss at make operation for different contact material combinations

Furthermore, contact material loss was determined by weighing the contacts before and after test. Material erosion at contact make is driven by the combination of bounce arcing and mechanical hammering. Figure 8 shows the specific erosion at make operation. This can be calculated by dividing the mass loss by the arcing energy at contact bounce.

Comparable erosion on movable and stationary contact can be observed for the symmetrical material combinations. Silver nickel shows the highest erosion values of the tested materials. Again, the values observed for the asymmetric material combinations of a movable AgNi10 and a stationary silver metal oxide contact are remarkable. Combining AgNi and Ag-SnO_2 results in almost identical material losses on both contacts, while the net material loss for the combination of AgNi and Ag-ZnO happens only on the movable (AgNi) contact. The material loss of an Ag-SnO_2 and Ag-ZnO combination is within the range of the symmetric ones.

The results for weld break forces and contact erosion of the asymmetric material combinations can be explained by looking on the cross sections of the tested contact pairs. The surface near microstructure after test for a movable AgNi10 and a stationary Ag-ZnO 92-8 combination is shown in Fig. 9.

Material migration from AgNi to Ag-ZnO can be found in the cross section. Therefore, the Ag-ZnO material doesn't show any net mass loss in the tested combination (compare Fig. 8). The contacts stick together after the bounce event at contact make and break within the AgNi texture at contact separation. This results in an AgNi surface layer on the silver metal oxide contact. Therefore, the weld break forces of the AgNi are dominant within this combination under the tested conditions. Analyzing the evaluation of weld break forces during the test one will find that after a short run-in period with lower values, weld break forces quickly increase onto the level of the symmetric AgNi combination.

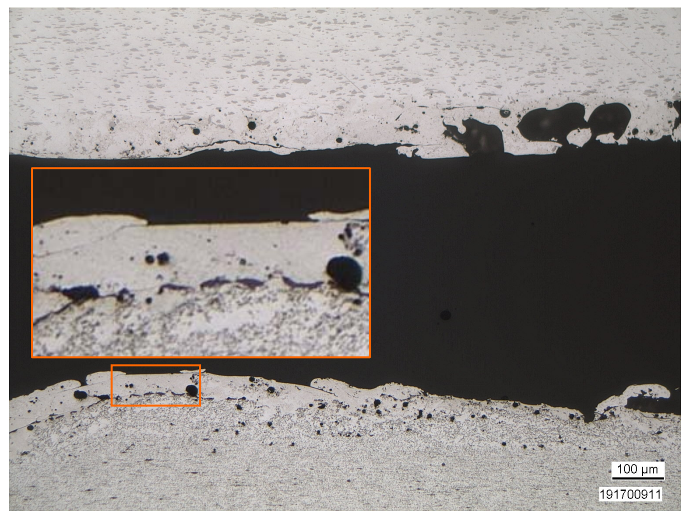

Figure 9. Cross section of AgNi10 (upper) and Ag-ZnO 92-8 (lower) after test

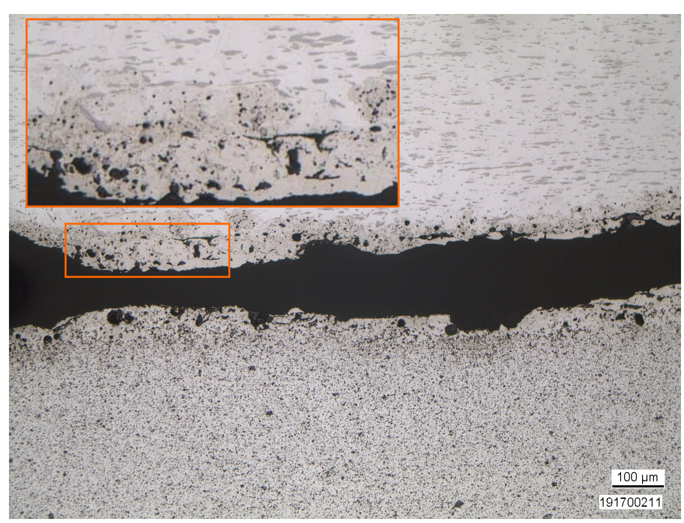

Figure 10. Cross section of AgNi10 (upper) and Ag-SnO_2 88/12 SPW7 (lower) after test

Figure 10 shows a cross section of a movable AgNi10 and stationary Ag-SnO_2 88-12 SPW7 combination after make-only model switch test. Here, material migration takes place in the opposite direction from the silver metal oxide to the silver nickel material. Thus, weld break forces quickly decrease from the AgNi level to the Ag-SnO_2 level within a few switching events during the test. Along with the metal oxide transfer onto the AgNi surface, welding during make bounce takes place in a porous, brittle and metal oxide enriched layer.

The cross section of the combination of Ag-SnO_2 to Ag-ZnO is illustrated in Fig. 11. A brittle, metal-oxide enriched surface layer, consisting of tin-zinc-oxides (dark grey phase), is formed during the bounce arc, which keeps the weld break forces on a moderate level.

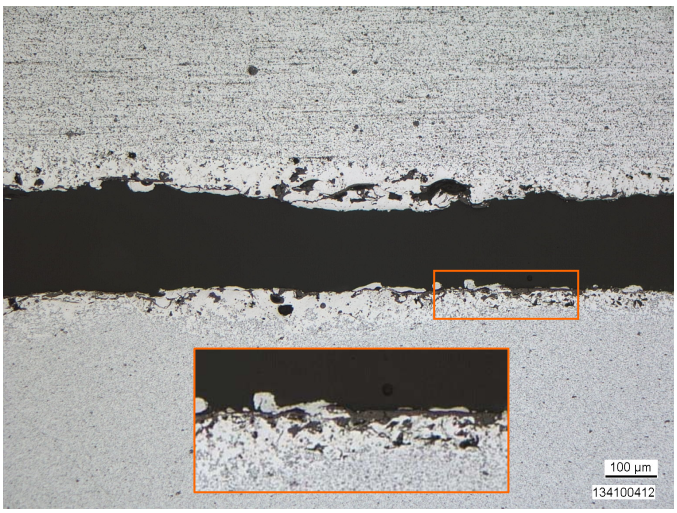

Figure 11. Cross section of Ag-SnO_2 88/12 SPW7 (upper) and Ag-ZnO 92-8 (lower) after test

IV. Summary

Contactors are widely used for control and remote switching purpose in industrial application. Typical contact materials are silver nickel and silver metal oxides. Endurance tests under heavy duty load proved the exponential relationship between arcing energy at break operation and contact material erosion. This correlation is essential for choosing the matching contact material volume. Furthermore, this dependency emphasizes the consequences on material erosion by upgrading switching capacities in existing device frames.

The positive effect of high total metal oxide contents on the erosion behavior under heavy duty load of silver tin oxide materials has been shown. The significantly reduced mass loss together with moderately increased temperature rises offers potentials for performance enhancement and precious metal saving.

Weld break forces have been studied as another important aspect for contact material selection. Special caution is necessary when choosing asymmetric material combinations of silver nickel and silver metal oxide. The combination of Ag-SnO_2 and AgNi showed intermediate weld break forces on a level between the two symmetric tests. But, combining Ag-ZnO and AgNi results in weld break forces on the high level of a symmetric AgNi application. This behavior can be explained by the brittleness of the different surface layers, created during bounce arcing at contact make.

Within this paper, experimental results on switching behavior of various contact material combinations were shown. These results can provide approaches for material selection in high performance switching devices, which fulfill the requirements of actual technological trends.

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