Basic Investigations on the Behavior of Advanced Ag/SnO_2 Materials for Contactor Applications

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Abstract

Higher power density and longer electrical lifetime at the same time are the main technical targets in development of contactors. Therefore, a close matching of contact material and switching device as well as the understanding of the material-device-interactions is necessary to achieve those demands. The paper will demonstrate the general influence of different material parameters based on Ag/SnO_2 in model switch tests and off-the-shelf contactors under various load conditions.

The basic tendencies of the materials can be seen in both test series, but are partially counterbalanced by device specific effects like electrodynamic lift-off, unbalanced erosion between single pairs of contacts or the rise in contact resistance. Since under different load conditions welding, erosion and contact resistance vary, contact materials with 12-14% metal oxide content and special additives appeared to be the best choice for contactor development.

Keywords: contactor, contact material, erosion, welding, resistance

1 Introduction

There are continuous trends for higher power density and longer electrical lifetime regarding switching devices. Nevertheless, different electrical load profiles have to be fulfilled, namely the various standardized utilization categories, like AC-3 or AC-4 in case of motor contactor applications. These different switching conditions require a compromise in design of the contactor itself and the choice of contact material as well. One of the key factors in modern switching devices, besides the switching behavior, is to keep the contact resistance on a certain level. This will be complicated by the fact that the mechanical contact forces per Ampere have to be lowered in order to meet power density and cost requirements. Therefore, a close matching of contact material and switching device as well as the understanding of the material-device-interactions are needed.

The making behavior is mainly influenced by the bouncing pattern of the contact system. In case of make capacity tests, bouncing can lead to contact welding [1] or contact levitation [2]. The contact resistance usually undergoes very little change after make capacity tests. During normal operation bouncing causes contact erosion and limits the lifetime of the contactor.

The breaking behavior, especially in break capacity tests, depends on arc running and quenching capabilities of the contactor. Usually much higher instantaneous values of current occur during breaking than during making. The contact material additionally influences the dwell time of the arc on the contacts and therefore also the whole arcing time. Increased arcing time as well as higher currents means higher energy input on the contacts and causes much higher contact erosion compared to contact making. In case of break capacity, the more important damage of the contact surface leads to a lower switching capacity performance compared to the make only conditions. Here again, contact welding or contact levitation are typical failure causes, occurring on the next make operation.

During lifetime-tests make and break switching phenomena are combined and additionally influenced by mechanical behavior of the contact material. So called "self-healing" effects can even occur by combination of make and break switching [3].

All these effects are not sufficiently understood in detail up to now; this means that a huge effort in development of new contactor generations is necessary. The paper will demonstrate some general interactions between contact materials, devices and different switching conditions.

In a first step, model switch tests are used, to show the general influences of different material parameters on the switching behavior, like weld break forces, erosion rates and contact resistance. Selected materials are then tested in off-the-shelf contactors under various load conditions.

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2 Influence of material parameters

The goal of these tests was to investigate the performance of different contact material compositions with respect to their fundamental characteristics like welding, erosion and contact resistance. For that we used model switches, described in [4, 5], as standard equipment to find material behavior independently of contactor properties. Welding forces are measured after making process only, while erosion and contact resistance are determined after breaking operation.

Contact materials based on Ag/SnO_2 are widely used in contactors for medium and high power range. Due to the above mentioned market requirements, however, Ag/SnO_2 will be increasingly used for smaller contactors. Therefore, these studies are focused on this material group. Low welding forces and erosion rates are the main advantages of Ag/SnO_2. On the other hand the contact resistance often rises with switching operations; this can be a serious drawback for devices with a higher power density. These characteristics are essentially influenced by the metal oxide content. Fig. 1 - 5 reveal these relations for Ag/SnO_2 without additives.

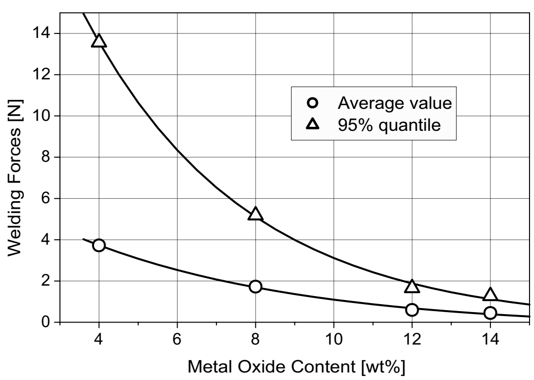

Fig. 1: Welding forces with respect to the metal oxide content ($I_{\mathrm{eff}} = 500$ A, 500 op.)

As expected, welding forces decline with increasing metal oxide content (Fig. 1), but the depicted exponential decay is also a result of a relatively low testing current. Micro welding happens in all configurations, but at higher oxide contents serious welding takes place more seldom and results in much smaller forces. Materials with higher oxide content only reveal their full potential at higher currents, as additional experiments have shown. Additives can weaken these welding forces, but bouncing pattern and total metal oxide content are dominant.

Also expected is a drop of the specific erosion rate Δm_{spec} (mass loss Δm with respect to arcing energy into the contact tips $E_{\mathrm{arc}} = U_{\mathrm{ac}} \int i \,\mathrm{d}t$) with an increased oxide fraction (Fig. 2). Explaining the decline of the absolute contact erosion Δm is a much

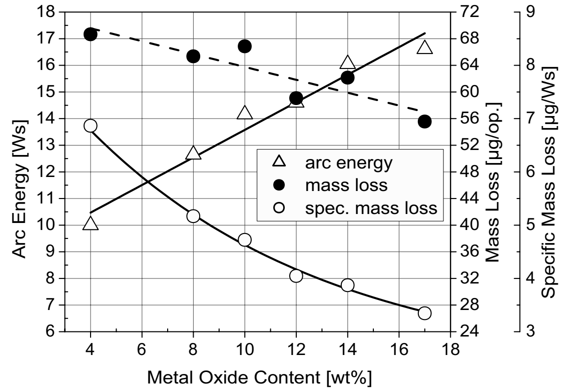

Fig. 2: Contact erosion and arc energy input with respect to the metal oxide content ($I_{\mathrm{eff}} = 250$ A, $B_{\mathrm{ext}} = 30$ mT/kA, 1000 op.)

more complex matter, especially in view of the increase in energy input E_{arc}. The higher arc energy is caused by lower arc root mobility and therefore longer arc duration with increasing oxide content [6]. This dwell time of the arc on the contacts can be separated into three phases: immobility during the initial contact opening, move to the contact edges, and finally hesitation on these edges [7]. After some switching operations, the immobility time and the velocity of the running arc are expected to dominate. Both values are depending on the material composition [8, 9], as well as device properties.

Thermal FEM-calculations with a moving arc root reveal that slower arc root movement limits the amount of molten volume (Fig. 3). Arcing is modeled as a constant heat flow into the arc root $\dot{Q} \equiv j_{\mathrm{arc}} \times U_{\mathrm{root}}$, as several authors suggested [10].

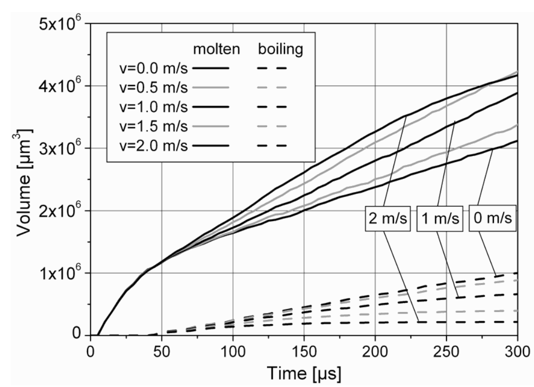

Fig. 3: Molten and boiling volume for a moving arc root ($A_{\mathrm{root}} = 0.04$ mm^2, heat flow $\dot{Q} = 1 \times 10^{10}$ W/m^2)

At all velocities, boiling takes place directly beneath the arc root, while molten volume adds up from volume beneath the root and the remaining volume behind the passed root. An increasing arc velocity decreases the energy input per surface area, which results in lower boiling volume, but much larger molten zones. Furthermore, a true arc would be able to impress higher heat flux densities for higher velocities, because of the cooler material in front of the arc root.

In these FEM-calculations fluid flow was neglected. In reality the build-up of molten zones is much more complex and additionally influenced by Lorentz forces, surface tension, pressure from the arc and density differences within the molten contact material [11, 12]. The oxide contents and additives influence viscosity and surface tension and therefore the flow velocity, as many authors describe, i.e. [13].

Fig. 4 show the results of a coupled electromagnetic, thermal and fluid-flow simulation, which takes pressure gradients from Lorentz forces into account for flow acceleration. This axisymmetric model considers the arc root as fixed. Arcing is modeled in the same way as before. However, free surface, and so surface tension and pressure from arc, is neglected. The goal of these calculations was to quantify the impact of different viscosity values for the molten contact material.

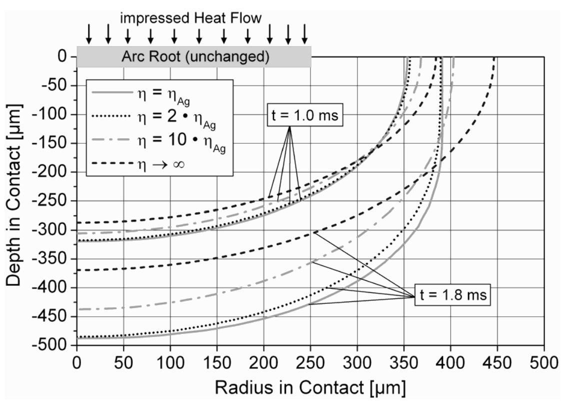

Fig. 4: Solid-liquid phase boundary in a contact tip for different viscosity values, at $t = 1.0$ ms and $t = 1.8$ ms ($R_{\text{root}} = 250$ μm, $I_{\text{DC}} = 250$ A, $\dot{Q} = 1 \times 10^{10}$ W/m^2)

The flow of contact material cannot influence the melting behavior until a certain quantity of molten material exists. Therefore only minor differences can be seen for different viscosity values for short arc durations (for instance in Fig. 4 at $t = 1.0$ ms). Only after longer arcing periods, the shape of the molten zone differs. Flow velocity increases and hence the molten pool will be deeper and smaller in case of lower viscosity. Also the molten volume increases slightly.

The flow velocity increases with the current I approximately in a linear fashion. At nearly constant current densities in the arc root j_{arc} [10], the maximal pressure $p_{\max}$ rises with the current $p_{\max} \propto \mu_0 \, I^2/(4\pi^2 R_{\text{spot}}^2) = \mu_0 \, j_{\text{arc}} \, I/(4\pi)$.

It can be concluded, that for small currents the fluid flow takes a secondary role. With increasing currents both the melting volume and the Lorentz forces increase about linearly, so flow velocities grow over-proportionally and the viscosity properties of the contact material becomes a major impact. In case of small oxide contents the high arc mobility and the low viscosity lead to larger molten volumes. This increases the possibility of splash erosion. It follows that an essential cause for lower erosion is the reduced role of splash erosion, while the amount of evaporation will remain at the same level.

This behavior is confirmed by the well-known increase of the mass loss Δm with respect to the energy input in the contacts with a power function $\Delta m \propto C_1 \times E_{\text{arc}}^{1.5\ldots3}$. Tests of Ag/SnO_2 materials with 12 and 14 % oxide content have shown, that the factor C_1 is changing, while the exponent is nearly constant. Additionally this relation is of course device-dependent.

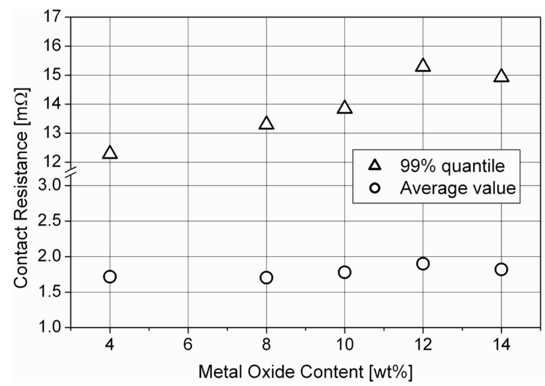

Fig. 5: Contact resistance with respect to the metal oxide content ($I_{\text{eff}} = 250$ A, 1000 op.)

A more astonishing result can be seen in the contact resistance (Fig. 5). The average contact resistance is little dependent from the oxide content, only the maximum values increase slightly. Metallographic slices reveal that the contact surfaces are contaminated by different oxide layers and carbon soot in all cases. There is no noticeable difference between the materials. Thus the development of contact resistance depends more on the switching process than the oxide contents. Additives are able to improve this behavior, but unfortunately not in general. Compared to new conditions the contact resistance is elevated for all materials.

3 Device-Material-Interaction

These tests with contactors are carried out to analyze the interaction of the contact material with the switching device and to evaluate their behavior under real life switching conditions. Required switching load conditions and typical resulting energy inputs and mass losses are shown in Tab. 1. All the following tests are carried out with these load conditions at a supply voltage of 400 V, $f = 50$ Hz and

Table 1: Comparison of various typical loads to be handled by contactors

load profile	background	load characteristic	num. of op. [–]	Energy E_{arc} [Ws]	mass loss Δm [μg/op.]
making cap.	extreme loads	on: $12\times I_r$, off: -	200	2 - 5	10 - 25
breaking cap.	overload	on: $10\times I_r$, off: $10\times I_r$	200	50 - 80	500 - 1500
short-circuit	short-circuit	3kA, with fuse	3	200 - 500	≤30.000
LT AC-3 22 kW	motor start	on: $6\times I_r$, off: $1\times I_r$	1.3 - 1.6 Mio	0.7 - 1	0.4 - 0.5
LT AC-3 30 kW	dito	dito	1.0 - 1.3 Mio	0.9 - 1.5	0.7 - 1
LT AC-4S 22 kW	reverse starting	on: $4\times I_r$, off: $4\times I_r$	100 - 200.000	10 - 12	8 - 13
LT AC-4S 30 kW	dito	dito	100.000	14 - 16	17 - 35

a power factor of $\cos\varphi = 0.35$[1].

All materials mentioned in Tab. 2 were made by powder metallurgical methods with an subsequent sintering and extrusion process. The materials feature a medium fineness. Additional tests with different finenesses or manufacturing methods of the SnO_2-powder confirm that the switching behavior can be improved for certain load cases. But allowing diverse load conditions which are typical for contactor applications, these materials are often not universally suitable.

Table 2: Tested materials and their compositions

name	ident	total oxide content	Additives Bi_2O_3	Additives WO_3
Ag/SnO_2	Mat1	8 wt%	–	–
Ag/SnO_2	Mat2	12 wt%	–	–
Ag/SnO_2	Mat3	14 wt%	–	–
Ag/Fe_2O_3	Mat4	6.4 wt%	–	–
Ag/SnO_2	Mat5	12 wt%	×	–
Ag/SnO_2	Mat6	12 wt%	×	×
Ag/SnO_2	Mat7	14 wt%	×	×

3.1 Switching capacity

Within these switching capacity tests, Ag/SnO_2 materials can demonstrate their strength regarding welding resistance and small mass loss. Compared to other contact materials at equal contact forces, Ag/SnO_2 shows mostly higher switching capacities. With regard to making behavior, this is a direct result of the better resistance against welding. Within this test series no quantitative differences could be seen with metal oxide contents in the range of 8% to 14%. Additives seem not to influence the results. Compared to other materials, like Ag/Ni, Ag/CdO or Ag/Fe_2O_3, contact levitation occurs more often as a consequence of the much better resistance against welding of Ag/SnO_2. It has to be mentioned that the making behavior is limited by the contactor design rather than the material properties.

The results of the breaking capacity tests reveal that the erosion behavior is more important than resistance against welding. Here, the kind of surface damage is deciding, and not the amount of material loss. Ag/SnO_2 surfaces typically develop a raise in the crater zone [2]. This results in smaller effective contact zones for the next making. Materials with higher oxide content work better in this regard, but additives downgrade the switching capacity under this test condition. Materials with very fine oxide grains or a better arc running behavior are able to improve the breaking capacity; however the experiments resulted in a broader scatter band.

A serious problem is the rise in contact resistance after such test series. Materials like Ag/Ni, Ag/CdO or Ag/Fe_2O_3 are showing much better results. Ag/CdO has to be mentioned as the best material in this category[2]. Not only does it show a relatively low rise in contact resistance, but also a very high breaking capacity due to the smallest energy entry and therefore only minor surface damage.

3.2 Lifetime tests

Regarding the lifetime tests, different erosion mechanisms occur in make-orientated (AC-3) and break-orientated (AC-4S) tests.

At AC-3 the mass loss at make and break operation is comparable. Certainly this distribution is highly dependent on the contactor model as a result of the bouncing and arc running behavior. Making and breaking form different surface topologies and material compositions at the surface. After make, the microscopic structure is rougher and the silver fraction higher. During breaking, even at lifetime tests according to AC-3, the melt zone extends much deeper, leading to higher oxide content near the surface and to coarser structures. Both processes combined can result in lower total erosion rates, but this is strongly dependent on the energy input ratio between make and break.

[1] Except breaking capacity tests are carried out with 550 V and lifetime tests according to AC-4S are done with a power factor of $\cos\varphi = 1$.

[2] Material runs as a benchmark only. According RoHS-policy Siemens decided not to use this material worldwide.

Specific mass loss Δm_{spec} of some materials is shown in Fig. 6. Here, an enormous influence of the different switching conditions is notable. The higher currents at break cause much higher specific mass loss compared to make-orientated tests.

An increase of the load in the AC-3 and AC-4S lifetime tests from 22 kW to 30 kW resulted in an average increase of the specific mass loss. However, with 31% at AC-3 the increase was less than the expected 40% (see section 2), while at AC-4S it even reached about 70%.

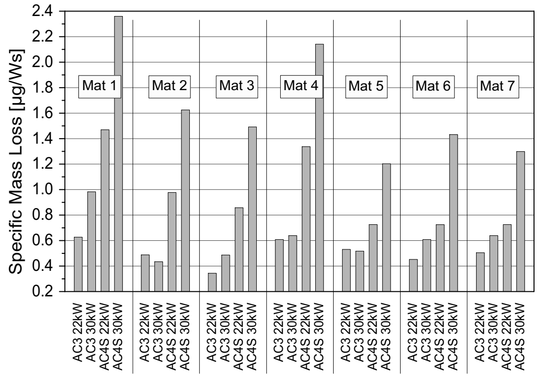

Fig. 6: Specific mass loss Δm_{spec} for some contact materials at different lifetime test acc. Tab. 1 (values are averaged over all contact tips and test examples)

In general, the specific mass loss Δm_{spec} declines with oxide content over all lifetime test series. This is in good agreement with the material tests in section 2. Nevertheless the influence of the additives is much more present, especially in case of AC-3. Often this can not be detected in the specific mass loss Δm_{spec}, but rather in the absolute mass loss Δm or finally in the number of attained operations.

Besides the electrically caused erosion there is an appreciable mechanical stress on the contact material and the bonding zone. This leads to cracks in the surface and in consequence to premature breakout damage. Especially materials with higher oxide contents or very fine grains suffer from this problem, so they are not suited in contactor applications.

In addition unbalanced mass loss of the six contact pairs was obtained as general lifetime limiting factor. This was not caused by the well known synchronism effect [1], but rather by mechanical tolerances of the contactor, uneven arcing behavior and by different erosion of the contact material. Typically one contact pair will erode faster than the other five, as shown in Fig. 7. Slight differences are being progressively amplified over the time of the test, as progressively higher energy input at make and break leads to more erosion. To quantify this effect, the highest mass loss of each contact tip was put in relation to the average mass loss of all twelve contact tips $C_{\Delta m} = \Delta m_i / \left(\frac{1}{n}\sum_i^n \Delta m_i\right)$.

The factors of unbalanced mass loss $C_{\Delta m}$ as displayed in Fig. 7 for each material could be reproduced relatively well, which leads us to believe that there is a certain influence of the contact material. Several additives show an improving influence with regard to this unbalanced mass loss, especially Bi_2O_3. But unfortunately there is no general rule for all additives and load conditions.

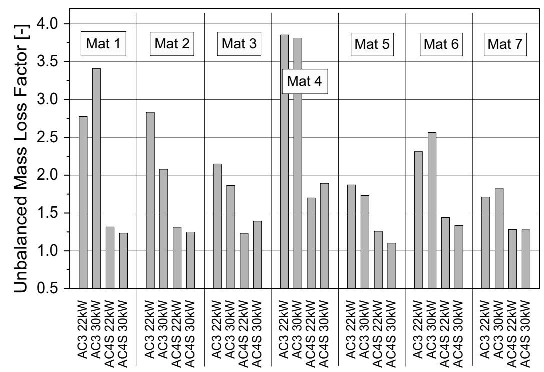

Fig. 7: Factor of unbalanced mass loss $C_{\Delta m}$ for some contact materials at different lifetime test acc. Tab. 1

Fig. 8 shows the influence of arc energy E_{arc}, mass loss per operation Δm, factor of unbalanced mass loss $C_{\Delta m}$, and lastly the product of mass loss Δm with the factor of unbalanced mass loss $C_{\Delta m}$ over the attained AC-3-lifetime at 22 kW load of 14 materials. The gradient of the regression line represents the influence on attained lifetime and the correlation gives the certainty to reach this extrapolated lifetime[3]. For a direct comparability all quantities are normalized.

It is astonishing that arc energy input[4] shows nearly no correlation to lifetime, at least within the spread of this load profile, although the difference is about 40%. Mass loss per operation Δm and unbalanced mass loss $C_{\Delta m}$ are similarly weighted. But if both quantities are linked, the highest influence and best correlation will be achieved. Fig. 8 also illustrates the wide range of possible lifetime values, although all materials are suited in general.

As mentioned above the rise of contact resistance is crucial factor in choice of contact material. At all tests the contact resistance increases by a factor between two to three (Fig. 9). The factorial relation between new and used state is nearly the same for all mathematical parameters like peak value, 95%-quantile or average value. Here again, the amount of oxide content is insignificant. Additives can lower the resistance in case of higher break loads, e.g. at AC-4S.

[3]All correlations are weak, any generalization should be considered carefully.

[4]Although only the making energy was measured, these values are representative because the breaking energy is very similar for all materials.

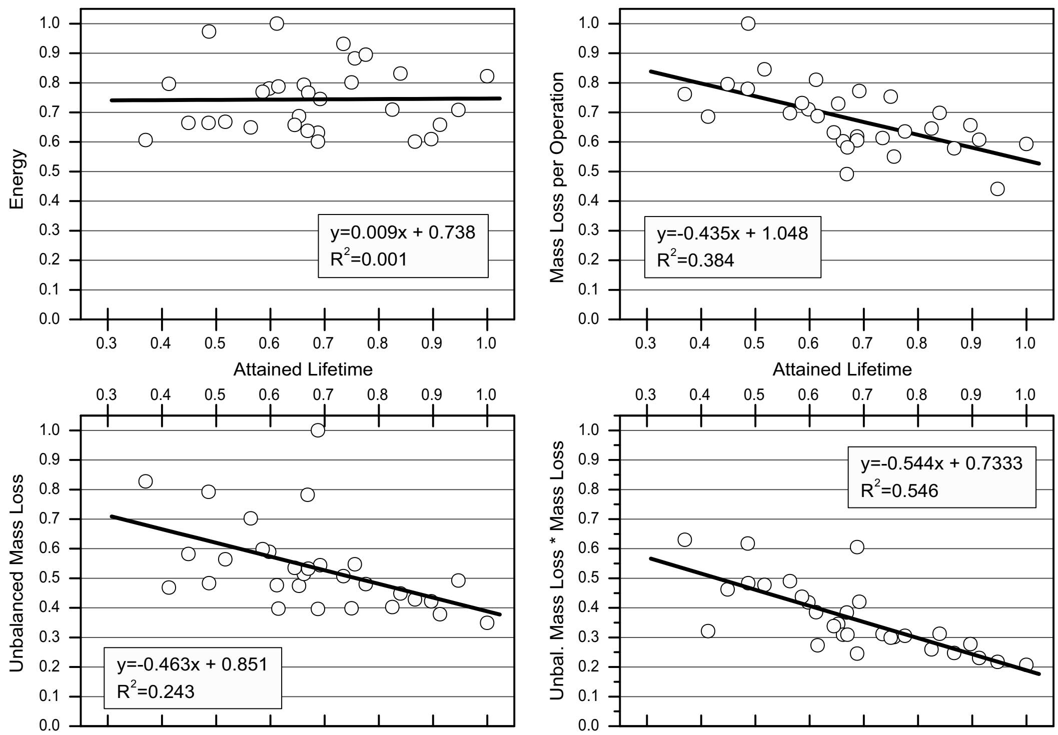

Fig. 8: Correlation functions of arc energy E_{arc}, mass loss per operation Δm, factor of unbalanced mass loss $C_{\Delta m}$, and the product of mass loss and the factor of unbalanced mass loss
(AC-3 lifetime tests at 22 kW load, 14 different materials, all quantities are normalized)

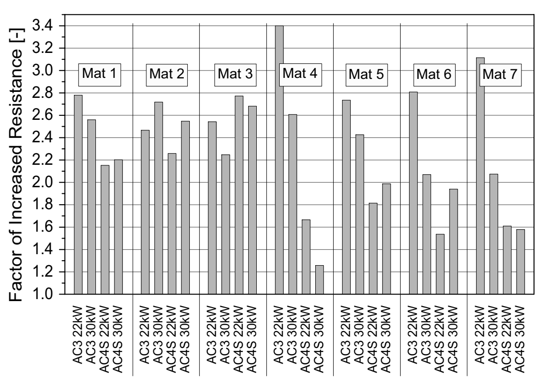

Fig. 9: Shift of the contact resistance after different life time tests with respect to new condition (95 % quantile of all measurements from several stages during the test)

4 Summary

Contact materials with higher oxide content have a better welding and erosion behavior. The decrease of contact erosion with increasing oxide content can be explained by lower arc mobility and higher viscosity values and therefore lower splash erosion.

The influence of different materials and load conditions on switching capacity, lifetime and contact resistance is demonstrated in model switch tests, as well as in 22 kW contactor device tests.

The basic tendencies of the materials could be seen in both test series, but are partially counterbalanced by device specific effects like electrodynamic lift-off, unbalanced erosion between single pairs of contacts or rise in contact resistance.

By quantitative analysis of device and contact material influences, these studies have identified unbalanced loading and material erosion rates as the key lifetime-limiting factors. Since under different load conditions these factors and contact resistance vary, contact materials with 12-14% metal oxide content and special additives appeared to be the best choice for contactor development.

Materials with higher oxide contents lower the erosion on the one hand, but tend toward cracked surfaces during lifetime tests on the other hand. This leads to mechanical disruptions and in turn to similar mass losses or attained lifetimes compared to materials with 12- and 14% oxide content. Compared to this, fineness or manufacturing method of the contact material are playing a subordinate role in view of the various load conditions which are typical for contactors in general purpose use.

The rise in contact resistance should be brought into focus, because this is the most limiting factor for devices with a higher power density. Additionally this would be an essential contribution to more environment-friendly devices.

5 Acknowledgement

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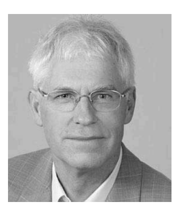

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