

# The Effect of Material Composition on Dynamic Welding of Electrical Contacts

Timo Mützel, Michael Bender, Ralf Niederreuther

Umicore AG & Co. KG  
Business Unit Technical Materials  
63457 Hanau-Wolfgang, Germany  
[timo.muettel@eu.umicore.com](mailto:timo.muettel@eu.umicore.com)

**Abstract**—The dynamic welding behavior at make operation is one important characteristic of electrical contacts and a key parameter to ensure secure usage of electricity. Model switch and device tests have been performed to work out the main factors influencing contact sticking. The behavior of different silver metal oxides (Ag/CdO, Ag/SnO<sub>2</sub>, Ag/ZnO), including various groups of additives like low melting and boiling metal oxides (Bi<sub>2</sub>O<sub>3</sub>), high melting oxides (CuO, WO<sub>3</sub>), and combinations thereof were studied under different loads.

Several working mechanisms – that significantly influence and define the sticking tendency – have been found for different arcing loads. They can be explained by metallurgical investigations and divided into mechanisms under low (below 0.3 Ws), medium (0.3 – 10 Ws), and high (above 10 Ws) arcing load.

The paper presents a scientific basis to explain contact sticking failures under different types of loads and can be seen as a guideline for appropriate contact material selection.

*contact material; weld break forces; contact sticking; silver metal oxide; additive*

## I. INTRODUCTION

Availability and security of electrical power are key factors in modern society. Switching devices and contact materials contribute essentially to fulfill this need. 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 [1] for direct switching of energy efficient machines, while devices are tested with 6 to 12 times rated current at make. Therefore, increasing requirements regarding the dynamic welding behavior at make operation, characterized by device bouncing pattern and increasing make currents, are postulated.

In parallel, the dynamic welding of contacts during make bounce is a key aspect for contact material development and selection. The knowledge on sticking mechanisms of typical contact materials in different load areas is basis for material selection within different applications and the main scope of this work.

## II. GENERAL TESTING ROUTINES

The dynamic welding behavior of different contact material combinations can only be studied under well defined and stable

boundary (bouncing) conditions. The bouncing event during make operation (Fig. 1) is defined by the current during arcing (especially instantaneously before contact re-closure), contact distance and therefore arcing mode, arcing/bouncing time, and contact force. Realistic values have to be realized for testing in different groups of applications (e.g. relays, contactor).

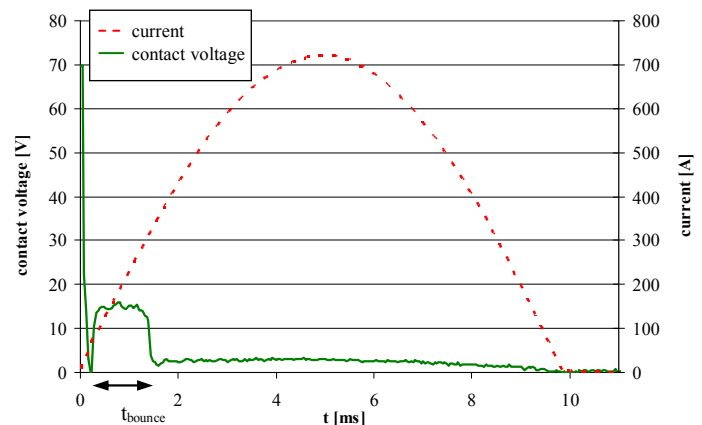


Figure 1. Voltage and current plot of make operation (model switch)

The average bounce arc energy at make  $W_{make}$  can be calculated by multiplication of the anode cathode voltage drop  $U_{AC}$  and the current integral for bouncing time  $t_{bounce}$  during testing from measurement values:

$$W_{make} = U_{AC} \int_{t_{bounce}} i(t) dt \quad (1)$$

For tests at  $U = 230$  V and inductive load or lamp load, the bounce arc time equals the mechanical bouncing time, as the arc does not extinguish.

Make-only model switch tests are performed, realizing a stable mechanical set-up and therefore constant bouncing time, peak current and bounce arc energy by synchronous switching. A detailed description of the hardware set-up and the performed test can be found in [2]. The tests are done with an alternating polarity of the electrodes to avoid influences by material migration.

All tested contact materials presented in this paper have been manufactured by powder metallurgical routine, via blending, compaction, extrusion, and rolling. The material compositions are given in weight percent (wt.-%).

### III. INFLUENCE OF METAL OXIDE CONTENT AND GRAIN SIZE

The influence of the total metal oxide content and the grain size of applied metal oxides on weld break forces was the first scope of this work. Tin oxide was selected as representative base metal oxide system for the studies. Make-only model switch tests have been performed with these Ag/SnO<sub>2</sub> materials applying electrical and mechanical parameters as summarized in Table I.

TABLE I. TEST PARAMETERS MAKE-ONLY MODEL SWITCH

Parameter	Value
voltage $U$	230 V
current (peak value) $\hat{i}$	700 and 1,300 A
power factor $\cos\phi$	0.35
closing velocity $v$	1 m/s
bouncing time $t_{bounce}$	1 ms
avg. bounce arc energy $W_{make}$	4.5 and 8.0 Ws
contact force $F$	3.5 N
number of operations $n$	300
contact diameter $D$	4.0 mm

Figure 2 is showing typical tendency on weld break forces for silver metal oxides from 4 to 14 wt.-% tin oxide (w/o additives). Results have been achieved in the described make-only model switch at test peak current  $\hat{i} = 700$  A and been published in [2, 3, 4].

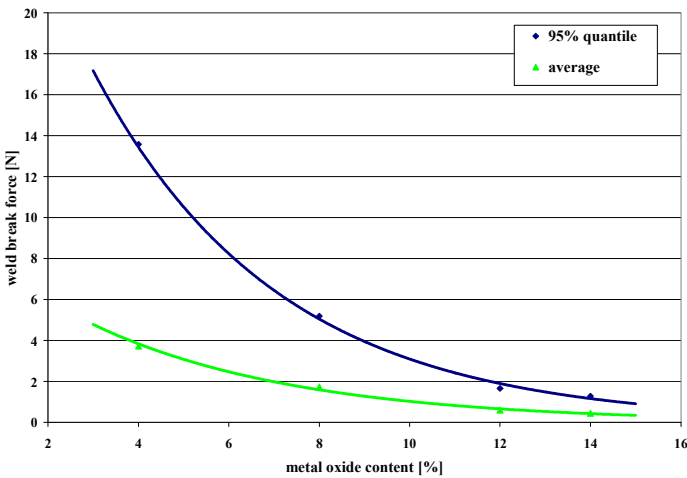


Figure 2. Weld break force as a function of tin oxide content

Weld break forces decrease with rising metal oxide content. The brittleness of the tin oxide enriched contact surface layer effectively prevents pure silver welding bridges and therefore reduces sticking tendency.

The influence of the grain size of tin oxide particles on weld break forces was studied in parallel to the above shown total tin oxide content. Therefore model switch tests with Ag/SnO<sub>2</sub> 88/12 and three different average particle sizes for SnO<sub>2</sub> have been performed. The resulting weld break forces at peak current  $\hat{i} = 1,300$  A are plotted in Fig. 3.

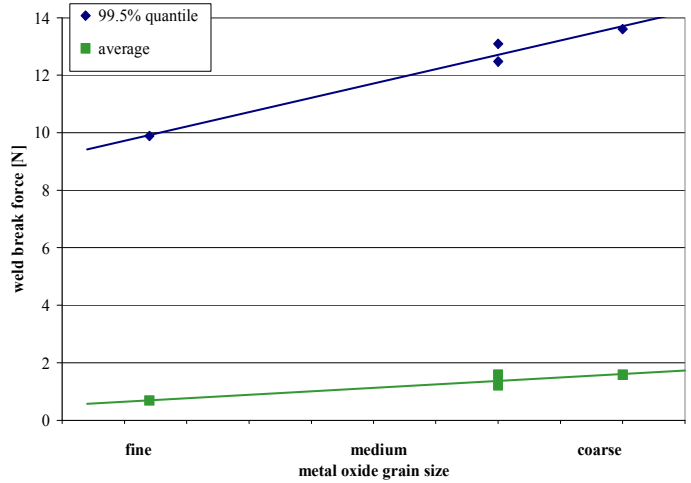


Figure 3. Weld break force as a function of average tin oxide grain size for Ag/SnO<sub>2</sub> 88/12

The regression of the average and 99.5% quantile is showing a linear increase of weld break forces within the range of investigated grain sizes. The more homogenous distribution within the surface layer and the larger surface area per volume of the finer tin oxide effectively reduces the weld break forces. This effect is valid as long as the comparatively high melting temperature of tin oxide is not reached in the arcing root, as melting and resolidification of the oxides would lead to a coarsening in the microstructure for all applied grain sizes (see Fig. 7). As this effect could also be achieved by longer burning break arcs, the influence of metal oxide grain size distribution on weld break forces can only rarely be found on make and break device tests.

### IV. EFFECTS OF METAL OXIDES AT LOW AND MEDIUM ARCING ENERGIES

Silver metal oxide contact materials are used as switching contacts in a wide range of applications covering, for example, relays, contactors, and circuit breakers. Depending on the particular application, different base metal oxides and dopant oxides are used. Typical contact materials (Table II), covering the studied application ranges, were selected for the following benchmark tests.

TABLE II. MATERIAL COMPONENTS

material	additives
Ag/CdO 90/10 SP	none
Ag/SnO <sub>2</sub> 88/12 SP	none
Ag/SnO <sub>2</sub> 88/12 SPW7	Bi <sub>2</sub> O <sub>3</sub> , WO <sub>3</sub>
Ag/SnO <sub>2</sub> 88/12 PMT1	Bi <sub>2</sub> O <sub>3</sub> , CuO
Ag/SnO <sub>2</sub> 86/14 PMT3	Bi <sub>2</sub> O <sub>3</sub> , CuO
Ag/ZnO 92/8 SP	none

Table III lists properties of metal oxides used and include silver as a reference.

TABLE III. METAL OXIDE PROPERTIES

Metal Oxide (Ag as reference)	Melting Point [°C]	Boiling Point [°C]
Ag	962	2,210
Bi <sub>2</sub> O <sub>3</sub>	817	1,890
CuO	1,326	2,000
WO <sub>3</sub>	1,473	1,700
CdO	1,559	1,559
SnO <sub>2</sub>	1,630	1,800 – 1,900
ZnO	1,975	1,975

Make-only model switch tests, applying different bounce arc energies, were performed, simulating the low and medium energy range. A description of test conditions is given in Table IV. The different bounce patterns, represented by the different contact forces and bounce arc times, were achieved by two mechanical set-ups (two types of model switches), which are optimized for the different device designs in those application areas. The differences in the chosen test parameters are due to the wide application range that should be covered by the tests. For realistic and practical testing, mechanical and electrical parameters had to be adjusted to typical values in the corresponding field of application, which is a prerequisite for best possible application related material selection.

TABLE IV. MODEL SWITCH TEST PARAMETERS

parameter	value			
peak current $i$	100 A	35 A	700 A	1,300 A
electrical load	lamp load	lamp load	inductive load	inductive load
contact force $F$	75 cN	75 cN	3.5 N	3.5 N
contact diameter $D$	3.0 mm	3.0 mm	4.0 mm	4.0 mm
number of operations $n$	2,000	5,000	300	300
avg. bounce arc time $t_{bounce}$	0.4 ms	1.5 ms	1.0 ms	1.0 ms
avg. bounce arc energy $W_{make}$	0.09 Ws	0.4 Ws	4.5 Ws	8.0 Ws

Weld break forces (99.5% quantile) over average bounce arc energy are shown in Fig. 4, being aware that arcing energy is only one and not the only physical aspect that influences contact sticking (see Section II, General Testing Routines). Each point represents one test series with number of operations  $n$  and corresponding number of force measurement points given in Table IV.

For different base metal oxides (w/o additives) highest weld break forces were measured for Ag/CdO 90/10, followed by Ag/ZnO 92/8 and Ag/SnO<sub>2</sub> 88/12. This partially results from the different metal oxides volume fractions applied in the materials (17.1 vol.-% for SnO<sub>2</sub>, 14.5 vol.-% for ZnO and 12.5 vol.-% for CdO). Nevertheless, it is well known that for the chosen field of application and corresponding test parameters, Ag/SnO<sub>2</sub> shows the lowest weld break forces, even at comparable metal oxide contents [5].

Weld break forces can be reduced by addition of combinations Bi<sub>2</sub>O<sub>3</sub> and CuO [3] or Bi<sub>2</sub>O<sub>3</sub> and WO<sub>3</sub> to the Ag/SnO<sub>2</sub> base matrix.

A relative weld break force was calculated for further studies on the influence of the average bounce arc energy at make operation on weld break forces. Therefore, the 99.5% quantiles of measured weld break forces have been divided by the average energy at make. This relative weld break force is plotted over the average energy at make in Fig. 5. Logarithmic scaling was necessary to illustrate the broad range of relative force values for the different material groups.

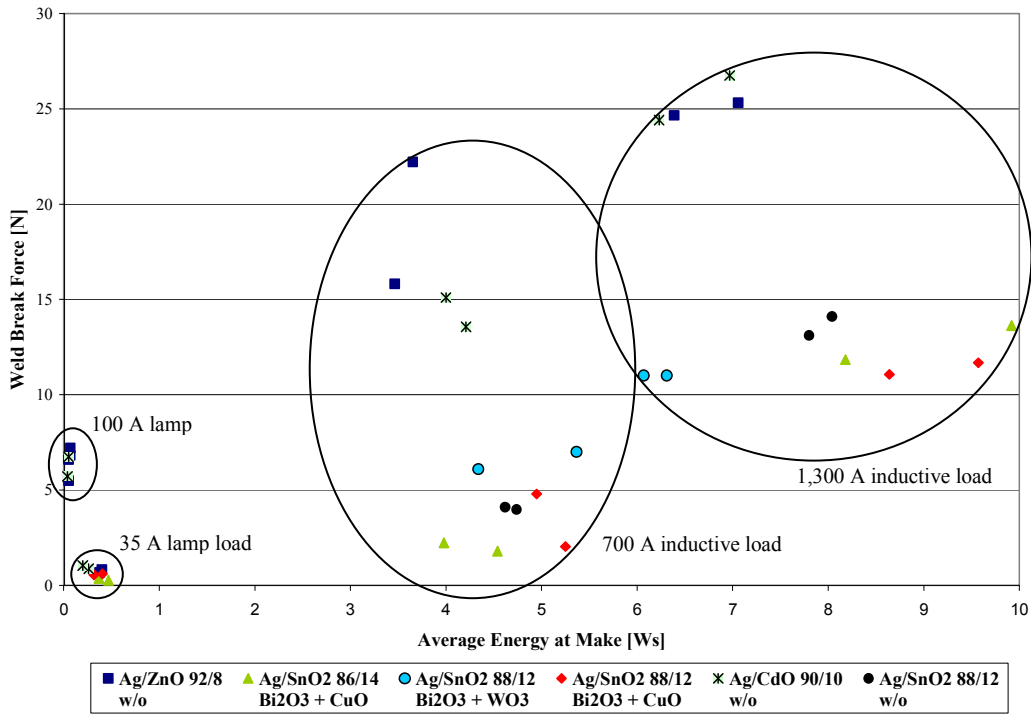


Figure 4. Weld break force as function of bounce arc energy for different silver metal oxide combinations

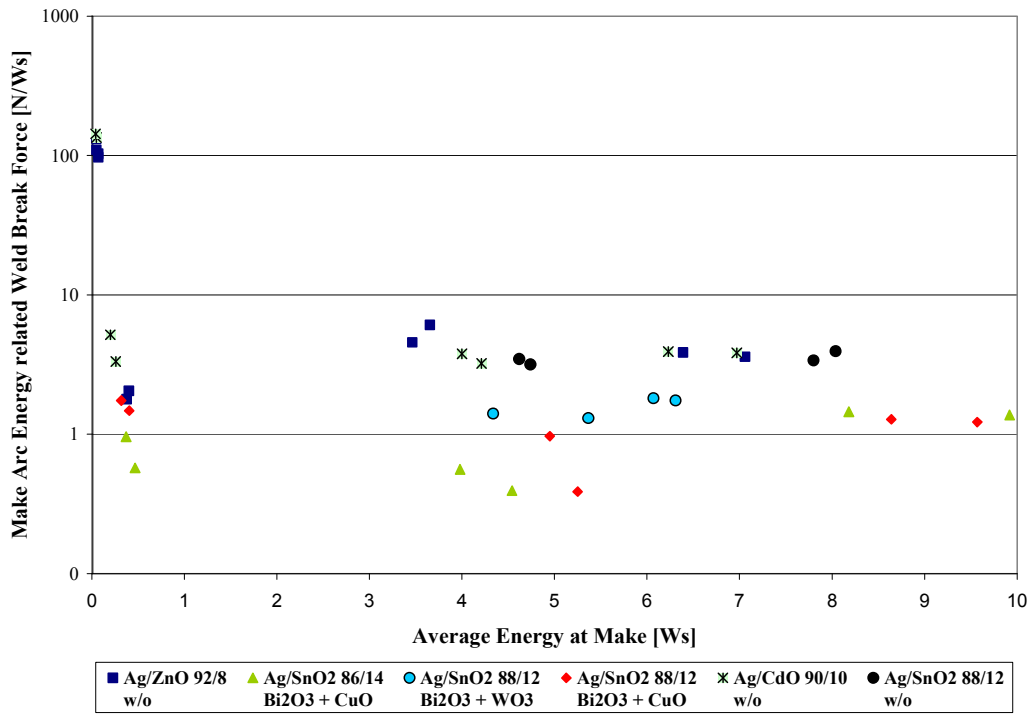


Figure 5. Relative weld break force as function of bounce arc energy for different silver metal oxide combinations

Almost constant relative weld break forces can be observed for the range from 0.3 Ws to 10 Ws average energy at make. But below 0.3 Ws, the relative weld break force is significantly increased. This behavior has been explained for Ag/Ni 80/20 by the different arc modes in [6]. The shorter bounce time and smaller bounce height come along with an anode arc, which causes narrow and deep melt spots, local evaporation of metal oxides (especially CdO sublimation on Ag/CdO materials), and therefore extremely high weld break forces. The cathodic arc creates wider and shallow molten areas due to micro-migration and therefore relatively lower weld break forces for longer bounce times and higher bounce heights.

In general Ag/SnO<sub>2</sub> with Bi<sub>2</sub>O<sub>3</sub> and CuO additions are showing lowest weld break forces up to 10 Ws bounce arc energy within the tested material combinations. This behavior can be explained by a closer look on cross sections of contact surfaces after test. Figure 6 is showing a Bi<sub>2</sub>O<sub>3</sub> layer on the surface of the upper contact piece, which creates an embrittling glassy phase, via energy dispersive X-ray spectroscopy (EDS). Low melting – with 817°C, the melting point of Bi<sub>2</sub>O<sub>3</sub> is below that of silver – and embrittling metal oxides like Bi<sub>2</sub>O<sub>3</sub> can effectively be used for a reduction of weld break forces in the medium arcing energy range.

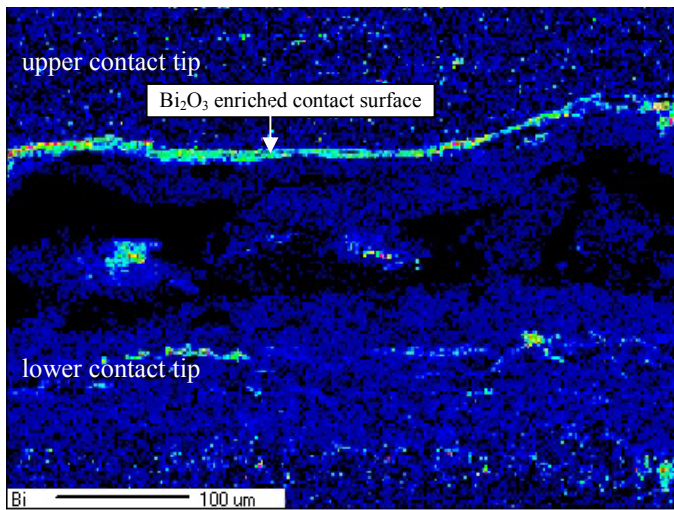


Figure 6. Bi<sub>2</sub>O<sub>3</sub> distribution (EDS ) on cross section after test showing concentrated Bi<sub>2</sub>O<sub>3</sub> line on contact surface

### V. WELD BREAK EFFECTS AT HIGH ARCING ENERGIES

In a next step, the effects on weld strengths at higher bounce arc energies at make (approx. 100 Ws), as they can appear on make capacity tests of e.g. large contactors, circuit breakers, or switch disconnectors, were studied.

Make-only test in accordance to IEC-60947-3 sequence 4 with a prospective peak current of  $i_{prosp.} = 50$  kA, current limited ( $i_{max} = 10$  kA) and interrupted by a 100 A rated current fuse, were performed. The behavior of Ag/ZnO and Ag/SnO<sub>2</sub> materials with different additives (Bi<sub>2</sub>O<sub>3</sub> and CuO) as representatives in this application field was compared.

No quantitative results for weld break forces are available here, as contacts could either be reopened by the operating mechanism or were heavily welded together.

Figure 7 is showing a cross section of an Ag/SnO<sub>2</sub> 88/12 (CuO additive) contact pair after test. The contacts were heavily welded together by the bounce arc and could not be opened after test. The CuO leads to a coarsening of the SnO<sub>2</sub> particles and additionally to a local reduction of the silver melting temperature at Ag-CuO interfaces during the bounce arc event. Thus, the weld break force and corresponding welding tendency is increased.

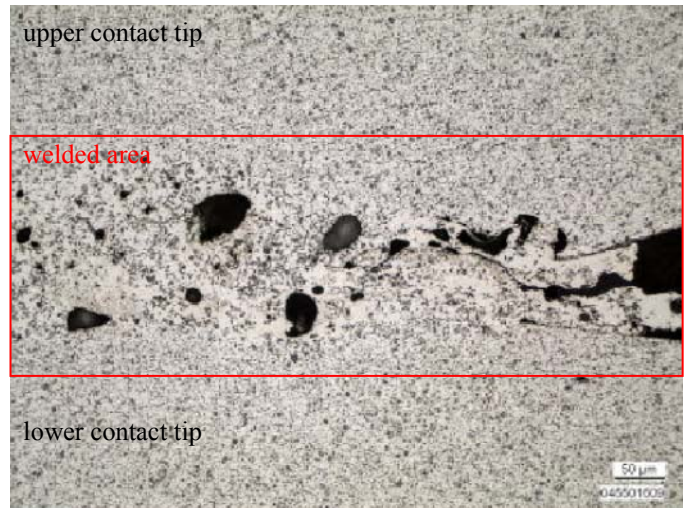


Figure 7. Cross section of Ag/SnO<sub>2</sub> 88/12 (CuO additive) after test

As a combination of Bi<sub>2</sub>O<sub>3</sub> and CuO additives effectively reduced weld break forces on Ag/SnO<sub>2</sub> 88/12 at medium arcing energies (section IV), the next test was performed with this material. But contacts were sticking together as tight as on the Ag/SnO<sub>2</sub>/CuO material before and could not be opened after switching test. A cross section of the contact pair after test is shown in Fig. 8.

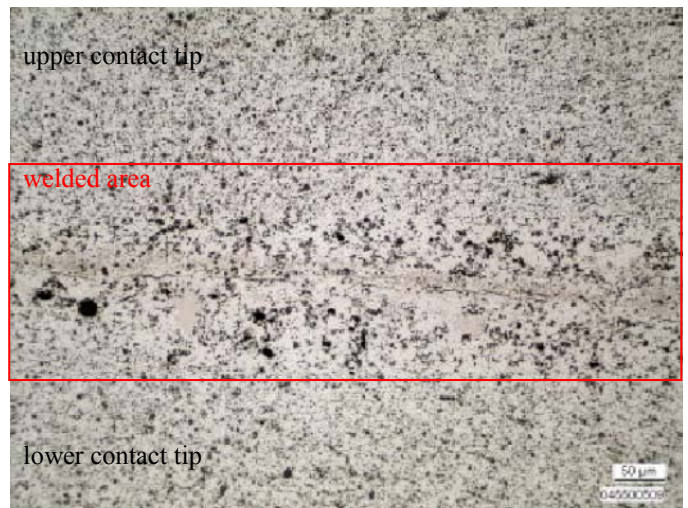


Figure 8. Ag/SnO<sub>2</sub> 88/12 (Bi<sub>2</sub>O<sub>3</sub> and CuO additives) after test



EDS measurements on welded Ag/SnO<sub>2</sub> 88/12 (Bi<sub>2</sub>O<sub>3</sub> and CuO additives) contact tips show a complete depletion of Bi<sub>2</sub>O<sub>3</sub> inside the welded area (Fig. 9). This loss of the welding inhibitor Bi<sub>2</sub>O<sub>3</sub> due to the high bounce arc energies leads to a strong welding of the composite material, compared to test at lower values (see Fig. 6).

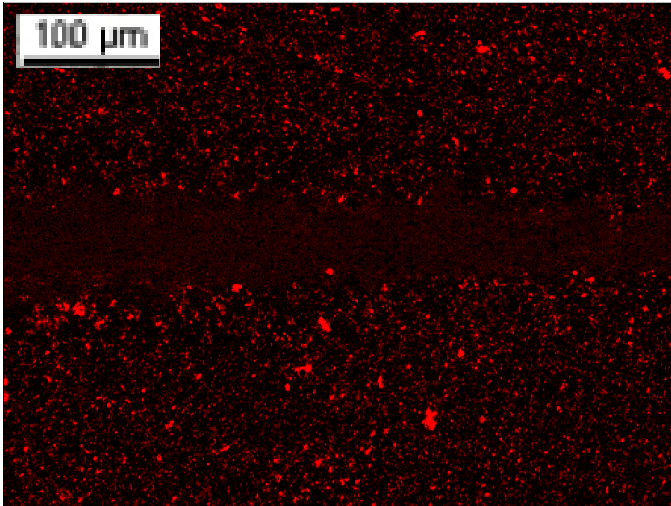


Figure 9. Bi<sub>2</sub>O<sub>3</sub> distribution (EDS) after test showing depletion in welded zone

For this reason, final tests were performed with Ag/ZnO 92/8, applying high melting/sublimating zinc oxide to the silver matrix (Table III). In this case the contacts could be separated after test. A cross section of the contact surface after test is given in Fig. 10.

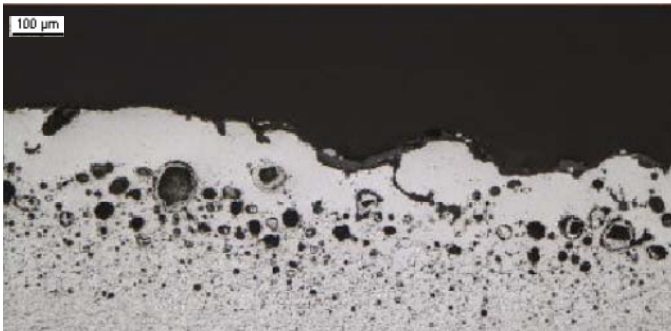


Figure 10. Cross section of Ag/ZnO 92/8 after test

Again, EDS was performed to analyze the element distribution after test. An EDS element mapping via atomic mass contrast is shown in Fig. 11 and the distribution of Zn in Fig. 12. Zinc oxide layers and pores, as reported for high energy break arcs in [7], can be observed in the arc influenced surface structure.

Thus, EDS mapping explains the anti-welding mechanisms on the Ag/ZnO contact material. In a first step, solid ZnO can be agglomerated on the contact surface, as the silver is molten, and can build up a brittle metal oxide enriched surface layer. And, if the bounce arc energy is high enough to reach the sublimation temperature of ZnO (1,975°C), the ZnO forms gaseous bubbles in the viscous silver melt. During cooling-down, the gaseous ZnO species recrystallizes on the inner walls

of the bubbles, leading to a thin film in a foam-like micro-structure, which can easily be broken on opening the contacts.

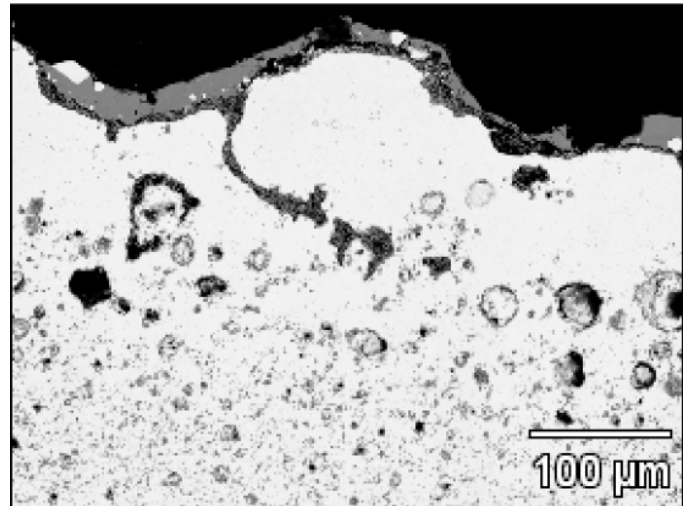


Figure 11. Atomic mass contrast (EDS) of Ag/ZnO 92/8 after test

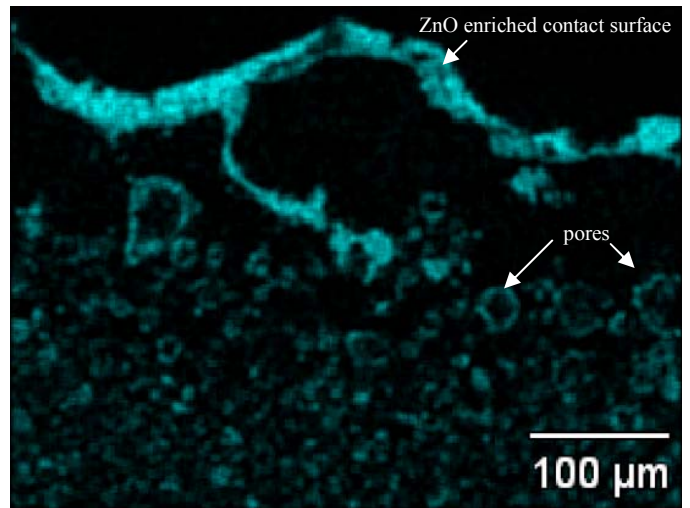


Figure 12. Zinc distribution after test (EDS) showing ZnO surface layer and bubbles

Consequently, the contact resistance of the Ag/ZnO probe after test has to be observed carefully, considering the ZnO enriched surface layer.

## VI. SUMMARY

The phenomenon of weld break forces for different application ranges has been studied by model switch and device testing. Achieved results were interpreted by metallurgical methods and the following dependencies of weld break forces have been worked out:

- The bounce arc energy is a key parameter for welding strength on make operation, as it defines the operation mode of materials used for reducing sticking tendency.

- Different base metal oxides and their total content are of significant influence for weld break forces. At low and medium arcing energies, SnO<sub>2</sub> seems to be superior to CdO and ZnO. Weld break forces can be reduced by increased total metal oxide contents.
- A finer dispersion of metal oxides within the silver matrix (microstructure) may be of advantage regarding weld break forces at low and medium arcing energies.
- Low melting additives like Bi<sub>2</sub>O<sub>3</sub> can effectively reduce weld strength at low and medium arcing energies by building up embrittling surface layers, while sublimating metal oxides (e.g. ZnO) leave bubbles within the microstructure and work better at high arcing energies.

Weld break force mechanisms of asymmetric material combinations have been presented in [8]. All presented effects have to be considered carefully for material selection during switching device development phase.

#### REFERENCES

- [1] Krätzschar, A.; Herbst, R.; Nothnagel, F.; Berger, F.: Kontaktschwebungen als limitierendes Phänomen beim Ein- und Ausschaltverhalten von Schützen. 19. Albert-Keil-Kontaktseminar, Germany, 2007
- [2] Mützel, T.; Braumann, P.; Niederreuther, R.: Experimental Investigations on Material Influences of Silver-Metal-Oxide Contact Materials for Contactor Applications. 54<sup>th</sup> International Scientific Colloquium (IWK), Ilmenau, Germany, 2009
- [3] Leung, C; Streicher, E.; Fitzgerald, D.: Welding Behavior of Ag/SnO<sub>2</sub> Contact Material with Microstructure and Additive Modifications, 50<sup>th</sup> IEEE Holm Conference on Electrical Contacts, Seattle, WA, USA, 2004
- [4] Chen, Z. K.; Witter, G. J.: A Study of Dynamic Welding of Electrical Contacts with Emphasis On the Effects of Oxide Content for Silver Tin Indium Oxide Contacts, 25<sup>th</sup> International Conference on Electrical Contacts (ICEC) & 56<sup>th</sup> IEEE Holm Conference on Electrical Contacts, Charleston, SC, USA, 2010
- [5] Mützel, T.; Niederreuther, R.: Advanced Silver-Tin-oxide Contact Materials for Relay Application, 26<sup>th</sup> International Conference on Electrical Contacts (ICEC), Beijing, China, 2012
- [6] Rieder, W.; Neuhaus, A.: Contact welding influenced by anode arc and cathode arc, respectively, 50<sup>th</sup> IEEE Holm Conference on Electrical Contacts, Seattle, WA, USA, 2004
- [7] Ambier, J.; Bourda, C.; Jeannot, D.; Pinard, J.; Ramoni, P.: Modification in the Microstructure of Materials with Air-Break Switching at High Currents, 15<sup>th</sup> International Conference on Electrical Contacts (ICEC) & 36<sup>th</sup> IEEE Holm Conference on Electrical Contacts, Montreal, Canada, 1990
- [8] Mützel, T.; Niederreuther, R.: Contact Material Combinations for High Performance Switching Devices, 58<sup>th</sup> IEEE Holm Conference on Electrical Contacts, Portland, OR, USA, 2012



**Timo Mützel** received the Dipl.-Ing. (2003) and the Dr.-Ing. (2008) degree 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, Germany. As Head of Applied Technology in the business line Contact & Power Technology Materials he is responsible for global technical customer support and applied technology. He is a recipient of the 2003 VDE Adam-Herbert-Prize.



**Michael Bender** received the Dipl.-Ing. (2006) and the Dr.-Ing. (2010) degree in Materials Science from the University of Saarland, Germany. From 2003 to 2006 he worked in the field of mechanochemical synthesis and electrophoretic deposition of ceramic nanoparticles at the Leibniz Institute for new Materials (INM) in Saarbrücken. In 2006 he joined the CVD department of Prof. Dr. M. Veith. In cooperation with the Fraunhofer Institute for biomedical engineering (IBMT) he focused on single source precursor-synthesis, chemical vapour deposition, CFD and photolithography. In 2010 he joined Umicore AG & Co. KG, Hanau, Germany. As a program manager he is responsible for research and development of Ag/SnO<sub>2</sub> contact materials.



**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 & Power Technology Materials and primarily engaged in experimental investigations on contact materials.