Contact Material Effects on Dynamic Contact Sticking

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Summary

The dynamic welding behaviour 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 behaviour of different silver metal oxides (Ag/CdO, Ag/SnO_2, Ag/ZnO), including various groups of additives like low melting and boiling metal oxides (Bi_2O_3), and combinations thereof were studied under different loads.

Two main 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. Low melting additives like Bi_2O_3 can effectively reduce weld strength at low and medium arcing energies by building up embrittling surface layers. This function is not given any more for high make arc energies or make operations on previous high energy break arcs, due to metal oxide depleted surface layers. Sublimating metal oxides (e.g. ZnO) leave bubbles within the microstructure and work better at high arcing energies.

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.

1 Introduction

Availability and security of electrical power are key factors in modern society. Switching devices and contact materials contribute essentially to fulfil 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 behaviour 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.

2 General Testing Routines

The dynamic welding behaviour of different contact material combinations can only be studied under defined and stable boundary (bouncing) conditions. The bouncing event during make operation is defined by the current during arcing (especially instantaneously before contact reclosure), 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).

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:

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

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.-%).

3 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, covering the studied application ranges, were selected for the following benchmark tests.

Make-only model switch tests, applying different bounce arc energies, were performed, simulating the low and medium energy range. An overview of test conditions is given in **Table 1**. 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.

Measured weld break forces (99.5% quantile) over average bounce arc energy are shown in **Figure 1**, being aware that arcing energy is only one and not the only physical aspect that influences contact sticking (see Section 2, General Testing Routines). Each point represents one test series with number of operations *n* and corresponding number of force measurement points given in **Table 1**.

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_2 88/12.

parameter	value			
peak current $\hat{\imath}$	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

Table 1 Parameters of make-only model switch tests

This partially results from the different metal oxides volume fractions applied in the materials (17.1 vol.-% for SnO_2, 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_2 shows the lowest weld break forces, even at comparable metal oxide contents [5].

Weld break forces can be reduced by addition of combinations Bi_2O_3 and CuO [3] or Bi_2O_3 and WO_3 to the Ag/SnO_2 base matrix.

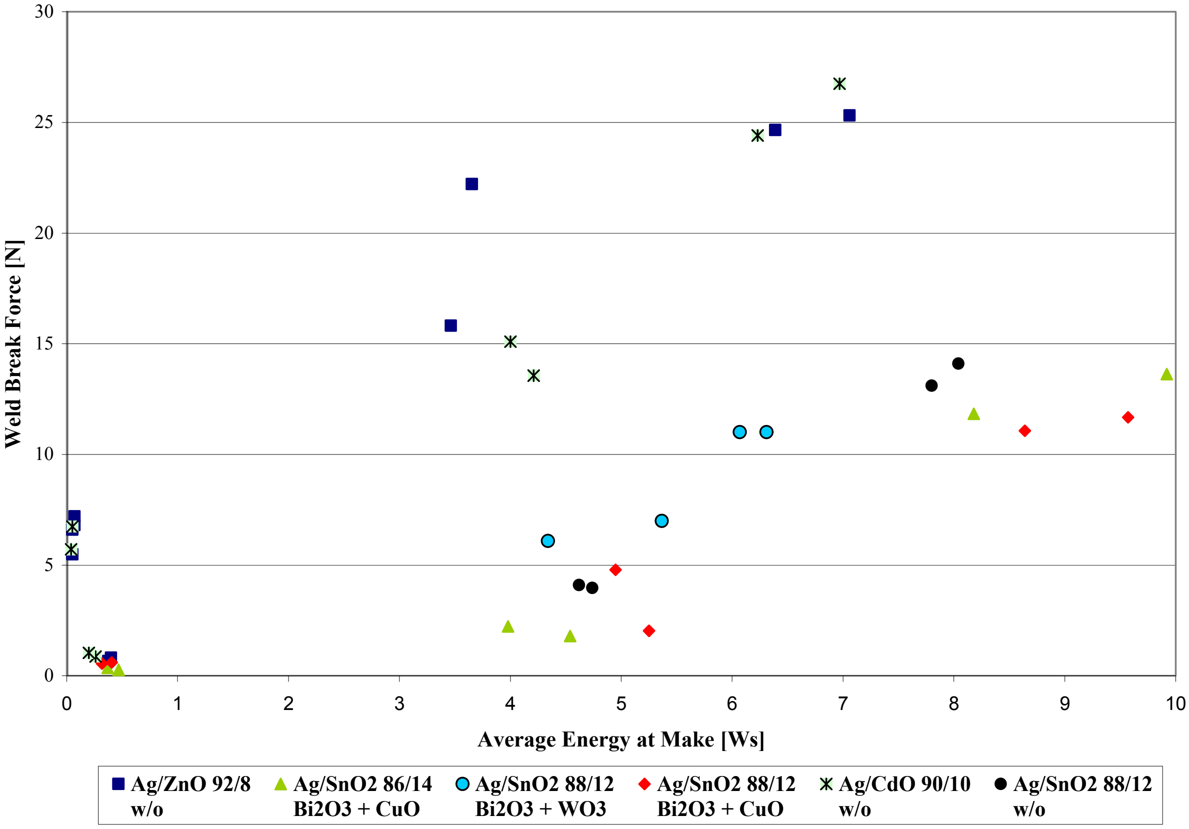

Figure 1 Weld break force as function of bounce arc energy for different silver metal oxide combinations

Almost linear increasing 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 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$_2$ with Bi$_2$O$_3$ and CuO additions are showing lowest weld break forces up to 10 Ws bounce arc energy within the tested material combinations. This behaviour can be explained by a closer look on cross sections of contact surfaces after test. **Figure 3** is showing a Bi$_2$O$_3$ 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$_2$O$_3$ is below that of silver – and embrittling metal oxides like Bi$_2$O$_3$ can effectively be used for a reduction of weld break forces in the medium arcing energy range.

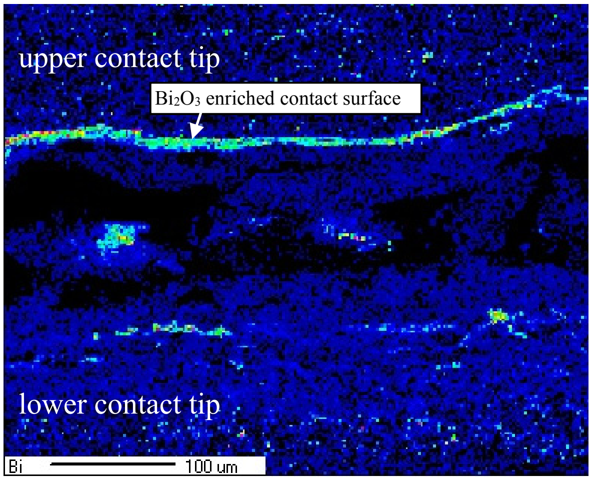

Figure 3 Bi$_2$O$_3$ distribution (EDS) on cross section after test showing concentrated Bi$_2$O$_3$ line on contact surface

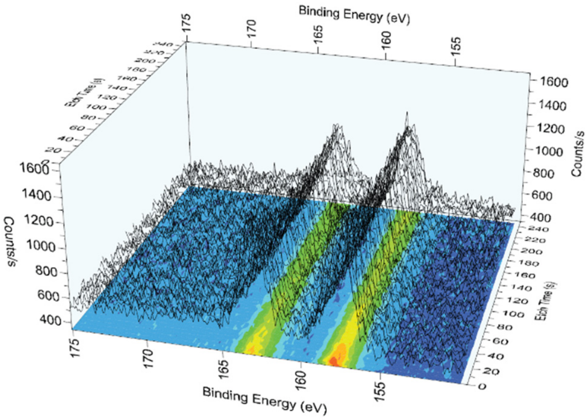

Figure 4 Bi (4f) 3-dimensional XPS-Scan

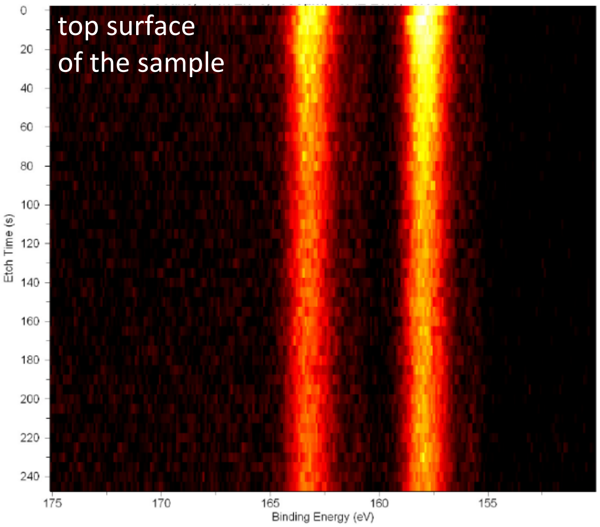

Figure 5 XPS measurements (2-dimensional projection)

Three-dimensional X-ray photoelectron spectroscopy (XPS) measurements on Bi$_2$O$_3$ containing contact materials (**Figure 4**) confirm the EDS results after switching. An argon plasma was used to etch the contact material in layers from its top into the bulk material. The two peaks used for the investigation of the volumetric Bi-distribution show the binding energies of the 4f (orbital) electrons. In the 2-dimensional projection of the analytical series (**Figure 5**) bright areas stand for high Bi-concentrations. In the near-surface area, we observed Bi$_2$O$_3$ enrichments with concentrations increased by a factor of 1.5 compared to the bulk material.

4 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.

4.1 Make-Capacity Tests

Make-only test in accordance to IEC-60947-3 sequence 4 with a prospective peak current of $\hat{\imath}_{prosp.}$ = 50 kA, current limited ($\hat{\imath}_{max}$ = 10 kA) and interrupted by a 100 A rated current fuse, were performed. The behaviour of Ag/ZnO and Ag/SnO$_2$ with Bi$_2$O$_3$ and CuO additives, as typical 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.

As a combination of Bi$_2$O$_3$ and CuO additives effectively reduced weld break forces on Ag/SnO$_2$ 88/12 at medium arcing energies (section 3), the test was performed with this material. **Figure 6** is showing a cross section of this material after test. The contacts were heavily welded together by the bounce arc and could not be opened after test.

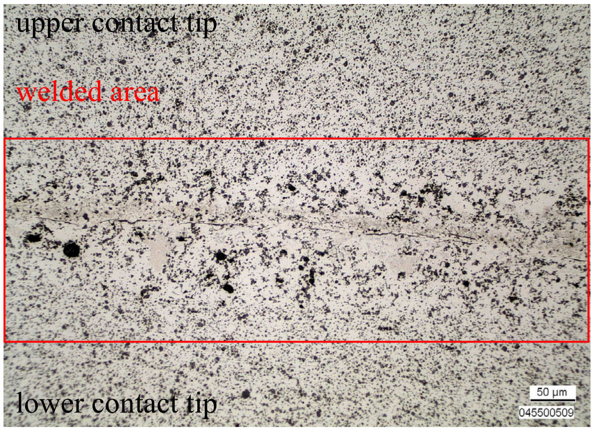

Figure 6 Ag/SnO_2 88/12 (Bi_2O_3 and CuO additives) after test

EDS measurements on welded Ag/SnO_2 88/12 (Bi_2O_3 and CuO additives) contact tips show a complete depletion of Bi_2O_3 inside the welded area (**Figure 7**).

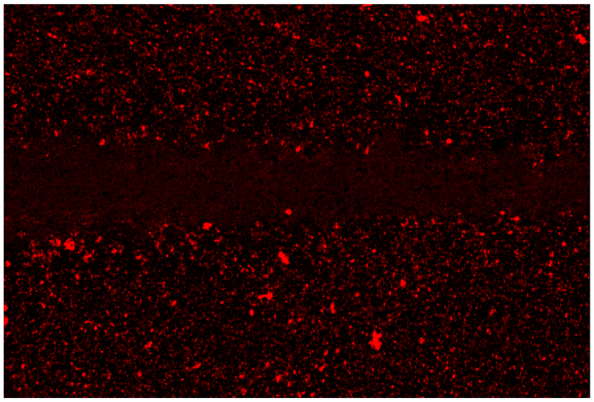

Figure 7 Bi_2O_3 distribution (EDS) after test showing depletion in welded zone

This loss of the welding inhibitor Bi_2O_3 due to the high bounce arc energies leads to a strong welding of the composite material, compared to test at lower values.

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

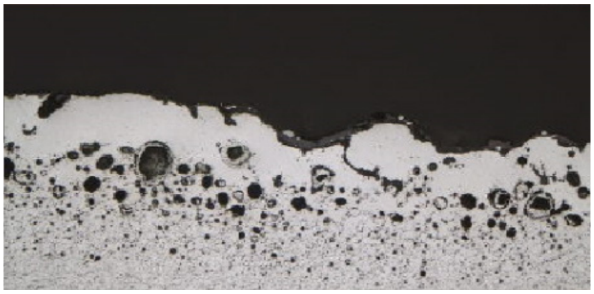

Figure 8 Cross section of Ag/ZnO 92/8 after test

Again, EDS was performed to analyse the element distribution after test. An EDS element mapping via atomic mass contrast was performed, and the distribution of Zn is shown in **Figure 9**. 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 microstructure, which can easily be broken on opening the contacts.

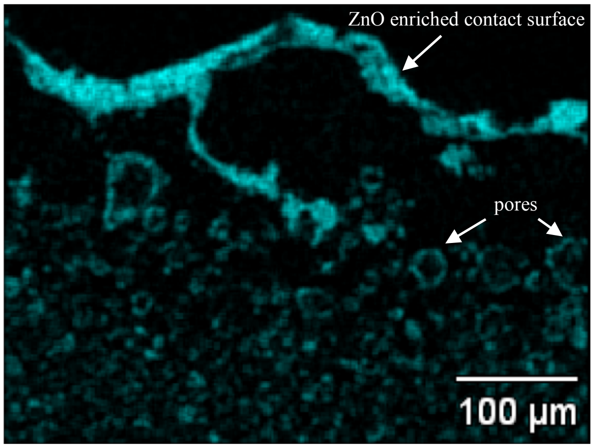

Figure 9 Zinc distribution after test (EDS) showing ZnO surface layer and bubbles

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

4.2 Switching Capacity Simulation by Pre-Conditioning

Another critical device test regarding contact sticking of silver metal oxide contacts in contactor application is rated making and breaking capacity test AC-3 in accordance to IEC-60947-4-1. The device has to pass 50 operations at 10 times rated current make-only, followed by 50 operations make and break at 8 times rated current. Typically, devices pass the first 50 operations make-only without problems, but sometimes fail due to sticking in the second 50 operations. Therefore, the sticking tendency seems to be significantly influenced by the break arc appearing in the second part of the test sequence.

A break-only model switch ($\hat{\imath}$ = 750 A, n = 30, W_{break} = 50 Ws) was used for pre-conditioning contacts to simulate the influence of break arcs on weld break forces at make operation. Subsequent make-only model switch test ($\hat{\imath}$ = 1,300 A, compare **Table 1**) applying the identical contact pairs were performed to quantify the effect. **Figure 11** is showing the weld break forces of Ag/SnO_2 materials with and without pre-conditioning by break arcs.

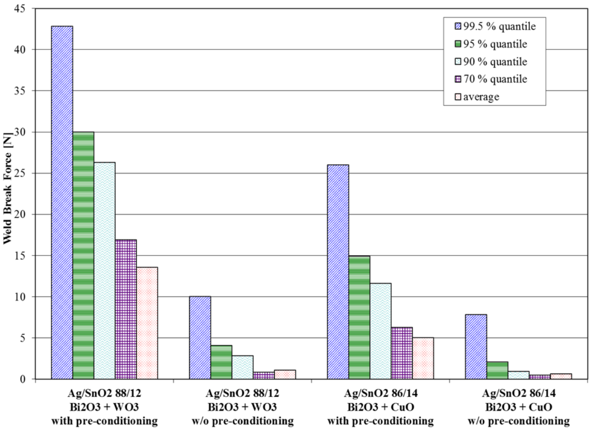

Figure 11 Weld break forces of Ag/SnO_2 materials with and w/o pre-conditioning

The measured separation forces of the Ag/SnO_2 86/14 material are lower compared to the 88/12 composition as already seen before (**Figure 1**) at low and medium arcing loads. The pre-conditioning of the contacts increases the weld break forces by factors of 5 – 10 in all quantiles. This result fits to those from device tests at make capacity (section 4.1) or switching capacity test.

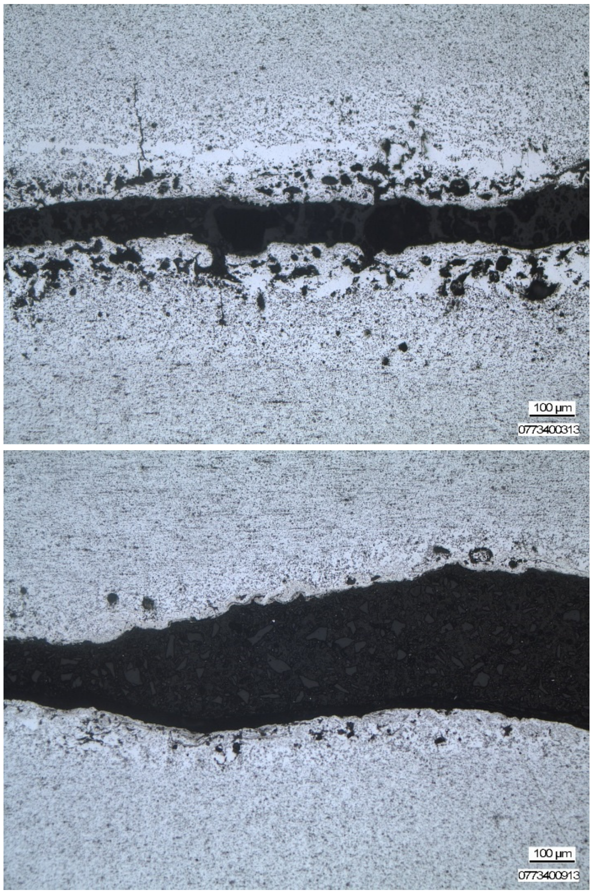

Figure 12 Cross sections Ag/SnO_2 86/14 (Bi_2O_3 and CuO additives) after test; with (upper pictures) and w/o pre-conditioning (lower pictures)

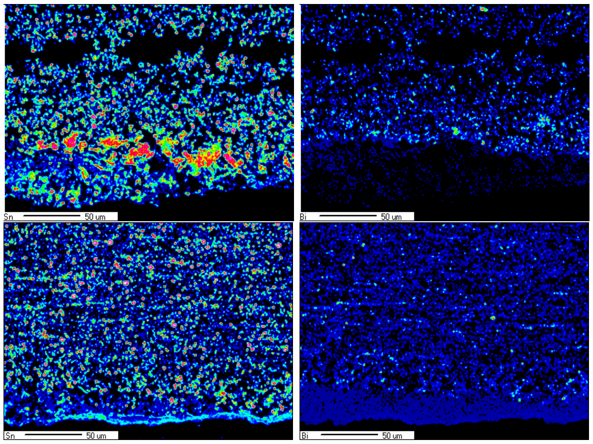

Figure 13 Sn and Bi concentration (EDS) after test; with (upper pictures) and w/o pre-conditioning (lower pictures)

Cross sections (**Figure 12**) of contact pairs after make-only model switch test with subsequent EDS mapping (**Figure 13**) were performed to explain the tremendous increase in weld break force by pre-conditioning break arcs. A significant difference can be seen in the arc effected zone close to contact surface. Those contacts, which have been pre-conditioned by break arcs show a porous and metal oxide depleted surface. In contrary the contacts which have been stressed with make-only have a smooth, dense, and metal oxide enriched surface. The EDS scan proves a surface layer (approx. 10 µm) with tremendous Sn and Bi enrichment on the contacts without pre-conditioning. A Bi_2O_3 depletion can be observed via EDS on the pre-conditioned contacts as a result of the break arcs, which can be considered as the main reason for the strong increase in weld break forces.

5 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 [8] are of significant influence for weld break forces. At low and medium arcing energies, SnO_2 seems to be superior to CdO and ZnO. Weld break forces can be reduced by increased total metal oxide contents [8].
- Low melting additives like Bi_2O_3 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.
- The function of low melting metal oxides (Bi_2O_3) regarding weld break force reduction is not given

any more for high make arc energies or make operations on previous high energy break arcs, due to metal oxide depleted surface layers

Weld break force mechanisms of asymmetric material combinations have been presented in [9]. All presented effects have to be considered carefully for material selection during switching device development phase.

6 References

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