Electro-mechanical properties of composite materials for high-current contact applications

This content has been downloaded from IOPscience. Please scroll down to see the full text.
(http://iopscience.iop.org/0022-3727/47/12/125501)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 129.194.8.73
This content was downloaded on 06/03/2014 at 15:37

Please note that terms and conditions apply.
Electro-mechanical properties of composite materials for high-current contact applications

J Jačimović1, L Felberbaum2, E Giannini1 and J Teyssier1

1 Département de Physique de la Matière Condensée, Université de Genève, CH-1211 Genève 4, Switzerland
2 Sécheron SA, Rue du Pré-Bouvier 25, CH-1217 Meyrin, Geneva, Switzerland

Received 7 November 2013, revised 12 January 2014
Accepted for publication 17 January 2014
Published 6 March 2014

Abstract
We report a detailed study that compares various composite materials (CM): Ag/ZnO, Ag/SnO2, Ag/C, Ag/WC, Ag/WC–C and Ag/Ni used in high-current dc circuit breaker applications. Their structural, mechanical, electrical and wetting properties were investigated. In parallel, switching operation tests on the same compounds were performed on commercial high-speed circuit breakers under real conditions (30 kA–900 V). A correlation between the microscopic variables and switching performances of the CMs was established. Materials like Ag/WC and Ag/WC–C were found to be unsuitable for the reliable functionality of the device. In contrast, Ag/C and Ag/SnO2 materials with high electrical and high thermal conductivity revealed remarkably good behaviour during switching operation tests.

Keywords: electrical contact materials, circuit breakers, material properties

1. Introduction

Low voltage electrical contact composite materials (CMs) based on a silver matrix have been used for many years in applications such as circuit breakers, contactors and relays. These devices work in various ways according to different issues faced during operation. In dc circuit breakers, the electrical contacts are in the closed state most of the time, enabling a low resistance path for the current. Nevertheless, in the case of a fast rise of the current (short circuit in the electrical network) they must move away from each other as fast as possible to interrupt the current flow. At that moment an electrical arc is created, and a considerable amount of energy (in the order of 1 kJ within 5 ms) is released at a very small spot on the surface of the contact material. The large resulting increase in the temperature (ΔT up to 2000° C) at the spot will cause local melting, possibly leading to sticking or welding of the two contacts. This local welding requires a larger force to open the contacts thus causing an attenuation of the device efficiency. To prevent sticking/welding events it was found that small particles must be dispersed in the silver matrix. Their role is manifold: to absorb a part of the arc energy through phase transition to reduce erosion of the contact material.
to have similar hardness and room temperature resistivity to Ag/CdO, but worse switching operation characteristics [13–15]. The addition of WC to the Ag matrix was found to increase the total hardness of the CM and to reduce room temperature conductivity, leading to an increase of sticking/welding events [16]. Finally, for the Ag/C CM the nature of the carbon allotrope (nano-particles, or nanotubes) changes the electrical (electrical/thermal conductivity) and mechanical properties of the silver matrix. The samples that contain carbon nanotubes showed the best electrical conductivity and lowest hardness [11, 12]. This CM was excellent for overcoming the welding issue but a fast degradation was observed [17].

CMs in which inclusions were homogeneously distributed had superior behaviour compared with those in which agglomerates a few micrometres large were present [18]. Regarding the preparation of CMs various techniques have been tested: powder metallurgy (PM), internal oxidation (IO) and the electroless coating method [16, 19].

Although the mechanical characteristics of various CMs are widely studied and a significant number of theoretical and experimental studies have been published over the last three decades [3, 18, 20, 21], to the best of the authors’ knowledge there are no studies which directly correlate the electromechanical properties of contact materials with performance behaviour in real operation tests.

The goal of this study is to correlate physical properties, such as electrical resistivity, thermal conductivity, hardness and wettability, to the performances of the compounds when used as contact materials. The physical characteristic measurements as well as real condition tests in a direct current (DC) circuit breaker were carried out on commercially available samples of different chemical compositions. The sticking/welding events, deviation of the contact resistance and temperature rise of the contact materials were monitored. The paper is organized as follows. Section 2 presents the materials used for the study as well as experimental techniques employed to study the physical properties of alloys and to perform switching operation tests. In section 3, we present experimental results. A relationship between the measured physical variables and the performances of the material under real operation conditions is discussed in section 4. Concluding remarks are given in section 5.

2. Materials and methods

The materials used in this study are commercial samples produced by Metalor and Doduco. In a silver matrix different particles such as CdO, SnO₂, ZnO, Ni, C (graphite), WC and WC–C (tungsten-carbide and graphite) were dispersed. We chose these seven types of inclusions since they are the most commonly used in high-current electrical contacts. It is important to mention here that a different Ag/dopant ratio is present in the samples (see table 1 for details).

For most characterizations we used samples shaped in a parallelepiped form with the dimensions 30 × 20 × 5 mm³. They were polished and the flat surfaces of the samples were maintained clean during all experiments. Powder x-ray diffraction measurements were carried out at room temperature using the 0–20 technique with Cu Kα radiations. The angle 2θ was ranged between 10 and 100° in steps of 0.02°.

A high resolution scanning electron microscope (HRSEM) (JEOL), with accelerating voltage ranging between 2 and 10 kV, was employed to analyse the surface morphology. Energy-dispersive x-ray spectroscopy (EDS) was used to map the chemical composition of the sample. The detection limit of the instrument was 1%, for elements whose atomic number is larger than that of oxygen.

The micro-hardness measurements were carried out by the Vickers method, using a diamond indenter. The measurements were carried out on polished surfaces. The force was applied for 30 s, and the applied load was varied between 300 and 500 g. No dependence on load was observed. The hardness of each material was measured at 20 different positions on the sample surface, and the final result is the arithmetic average. Additionally, all samples were subjected to a soft annealing procedure (heated for 2 h at 600 °C, in argon environment), and the micro-hardness measurements were then repeated.

Differential thermal analysis (DTA) and thermal gravimetric analysis (TGA) were carried out simultaneously using the TAG 24 SETARAM experimental set-up. Samples of about 50 mg were placed in alumina crucibles. The sample was heated up to 1500 °C at 5 °C min⁻¹, then cooled down to 500 °C at the same rate and the thermal cycle was repeated twice, under an atmosphere of 80% Ar–20%O₂ (see figure 4(a)). For the Ag/C sample, a different cycle with Tmin = 200 and Tmax = 1100 °C was used.

The solid/liquid adhesion energy Wsl was measured using the contact angle method [22]. The procedure is based on Young’s equation [23]:

\[ \gamma_S = \gamma_{sl} + \gamma_1 \cos \theta \],

which relates liquid surface energy γ₁, solid surface energy γ₀, solid–liquid interface energy γsl. Bearing in mind that adhesion work between liquid and solid is defined as [22]

\[ W_{sl} = \gamma_1 + \gamma_S - \gamma_{ss} \]

we easily find out the relation between Wsl and measured contact angle:

\[ W_{sl} = \gamma_1 \left(1 + \cos \theta \right) \].

In order to distinguish the polar and dispersive parts of Wsl precisely, three different solvents were used: distilled water, diiodomethane and formamide (see table 2). The estimation was carried out using the Fowkes method [24]. Finally, knowing the polar and dispersive part of the liquid solid adhesion energy, wetting envelopes (WEs) were constructed. In the coordinate system made from the polar and dispersive part of the liquid surface tension the envelope defines the line where the condition (cos θ = 1) is satisfied. All liquids whose surface energy falls inside the WE will consequently wet the solid surface.
Table 1. Mass and volume percentage of an additional component in the silver matrix, and the method used for the preparation of the composite materials; hardness values of various CMs, measured by Vicker’s method; room temperature electrical resistivity expressed in IACS, RRR—room temperature resistivity normalized on a value at 5 K, calculated electronic contribution of thermal conductivity at room temperature; number of switching operation tests, number of sticking and welding events, and the temperature rise of contact materials.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight %</th>
<th>Volume %</th>
<th>Preparation method</th>
<th>HV Hardness (kgf mm(^{-2}))</th>
<th>Soft annealed HV Hardness (kgf mm(^{-2}))</th>
<th>(\rho_{\text{el}}) ((\mu\Omega\cdot\text{cm}))</th>
<th>IACS (%)</th>
<th>RRR</th>
<th>Number of tests</th>
<th>Sticking</th>
<th>Welding</th>
<th>Deviation rise (T_c) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>10.0</td>
<td>12.5</td>
<td>Internal oxidation</td>
<td>91.3 \pm 3</td>
<td>69.2 \pm 2</td>
<td>2.065</td>
<td>85</td>
<td>37</td>
<td>348</td>
<td>1</td>
<td>No</td>
<td>22</td>
</tr>
<tr>
<td>CdO</td>
<td></td>
<td></td>
<td>Powder metallurgy</td>
<td>44.1 \pm 1</td>
<td>33.1 \pm 1</td>
<td>2.457</td>
<td>70</td>
<td>28.4</td>
<td>292</td>
<td>31</td>
<td>No</td>
<td>34</td>
</tr>
<tr>
<td>AgC</td>
<td>12.0</td>
<td>21.6</td>
<td>Powder metallurgy</td>
<td>86.1 \pm 1</td>
<td>80.2 \pm 2</td>
<td>2.503</td>
<td>71</td>
<td>19.6</td>
<td>287</td>
<td>32</td>
<td>No</td>
<td>88</td>
</tr>
<tr>
<td>SnO(_2)</td>
<td>10.0</td>
<td>17.0</td>
<td>Powder metallurgy</td>
<td>67.3 \pm 3</td>
<td>60.3 \pm 3</td>
<td>1.876</td>
<td>95</td>
<td>60</td>
<td>391</td>
<td>31</td>
<td>No</td>
<td>103</td>
</tr>
<tr>
<td>ZnO</td>
<td>20.0</td>
<td>14.4</td>
<td>Powder metallurgy</td>
<td>107.2 \pm 2</td>
<td>60.2 \pm 2</td>
<td>2.655</td>
<td>66</td>
<td>17.1</td>
<td>271</td>
<td>15</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>WC</td>
<td>20.0</td>
<td>14.4</td>
<td>Powder metallurgy</td>
<td>103.3 \pm 3</td>
<td>63.2 \pm 3</td>
<td>2.453</td>
<td>71</td>
<td>20</td>
<td>293</td>
<td>36</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>WC-C</td>
<td>30.0</td>
<td>33.5</td>
<td>Casting</td>
<td>99.1 \pm 1</td>
<td>73.2 \pm 3</td>
<td>4.458</td>
<td>39</td>
<td>12.2</td>
<td>160</td>
<td>15</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

For resistivity measurements small samples with dimensions of 5 \(\times\) 2 \(\times\) 0.2 mm\(^3\) were prepared and contacted with silver paste. The measurement was carried out by employing the standard four-point method in the 300–4.2 K temperature range.

All materials used in this study were subjected to switching operation tests. These tests were conducted on a commercial dc high-speed circuit breaker in a specialized laboratory which is able to reproduce the harshest service conditions. The contact materials were exposed to dozens of cycles (the exact number is presented in table 2) under the same conditions (33 kA, 15 ms, 750 V, corresponding to sequence T2 of IEC60077 standard). The mechanical time and peak current were recorded for each current interruption, whereas the resistance was measured at the terminal of the HSCB after each O–CO–CO sequence. The standard deviation of the latter data is given in table 1. Sticking and welding events are directly linked to the mechanical time and peak current.

3. Results

3.1. Mechanical and electrical properties of contact materials

3.1.1. X-ray diffraction. The x-ray diffraction spectra of various samples are presented in figure 1. The measured data of CMs demonstrate that in each sample only two different phases are present: silver (Ag peaks marked in figure 1) and corresponding inclusions (CdO, ZnO, SnO\(_2\), Ni, C, WC and WC–C). No additional impurity phases were detected within the detection limit of 1%.

3.1.2. HRSEM and EDX. The high resolution scanning electron microscopy (HRSEM) images of the investigated samples are presented in figure 2. The surface morphology was systematically analysed in great detail in order to better understand the way the dopants are distributed in the host matrix. Different magnifications are chosen to reveal the detailed microstructure of each sample having different morphologies, depending on the manufacturing process. We observed the existence of an Ag matrix and ‘islands’ made of dopants. The Ag percolation paths ensure low electrical resistance of the samples, which will be discussed later in the paper.

Figure 1. XRD spectra obtained for the Ag sample doped with different elements.

We further found out that the dopant islands have a random (which could be a consequence of the agglomeration of inclusions) or elongated (due to extrusion) shape. Our analysis shows that the radius of the agglomerates varies. By classifying
alloys with respect to this parameter we find that all our samples fall into two sets: (i) Ni, regions with average size larger than 2 \( \mu \)m, and (ii) CdO, SnO\(_2\), ZnO, WC and C regions with a radius smaller than 2 \( \mu \)m.

3.1.3. **Micro-hardness.** The results of the micro-hardness measurements are summarized in table 1. The values vary between 20 HV for the softest sample of pure silver to 110 HV for the hardest alloy of Ag/WC. The common feature is that all dopants significantly increase the original hardness of the silver matrix in agreement with previously reported data [26]. The increase in hardness might be related to the nature of the dopants themselves, their size and distribution in the silver matrix. Namely, WC is known to be hard, and Ag/WC shows the highest hardness among the tested samples before the soft annealing. Graphite is soft and may act as a solid lubricant at grain boundaries resulting in Ag/C being the softest CM in our study.

We performed a soft annealing treatment (as explained in section 2) mimicking the conditions that the contact materials experience during their life. This makes it possible to compare the samples used for the characterization with those practically used in the circuit breakers. During the brazing of the contact material on the device or during operation (after the appearance of an arc or a current rise), a contact material experiences a huge increase in temperature, which can release the internal stress and thus reduce the initial hardness (table 1). We see that the hardness of all CMs is lowered, and the ranking between the samples is not the same any more. Ag/Ni and Ag/SnO\(_2\) CMs appear to be harder than Ag/WC and Ag/WC–C. Therefore, one can conclude that the increase in hardness is not only related to the nature of the dopant but also to the structural defects.

3.1.4. **DTA and TGA.** The thermodynamic behaviour of the CMs was studied by means of DTA and TGA. Thermograms, in general, show if a material undergoes transitions upon rising or lowering temperature. They provide an insight into the silver and dopant thermodynamic and chemical stability at temperatures as high as those achieved during the presence of an electric arc.

The DTA profiles of pure silver and CMs are presented in the limited temperature interval, 850–1000 °C, in figure 3. The graph shows that in all DTA profiles recorded during the first heating, the temperature of the endothermic peak associated with the melting of silver varies between 950 and 970 °C.

TG profiles are presented in figure 4. Data of pure silver and of the CM with oxides is plotted in the 1000–1500 °C
temperature range, while those of Ag/C are depicted from 20 to 1100 °C. Figure 4(b) shows that pure silver loses 33.6% of its mass during the thermal treatment described in figure 4(a). Most of the mass loss appears at temperatures higher than 1300 °C by evaporation. Measurement at this temperature is of particular importance since the temperature on a material in operation can reach 2200 °C at arc roots (the boiling point of the silver host matrix). The various CMs Ag/oxide also reveal a remarkable weight loss. The total mass losses (silver plus second phase) of Ag/SnO2, Ag/ZnO and Ag/CdO are 35.5%, 34% and 32.5%, respectively. Ag/SnO2 and Ag/ZnO have the same trend as the pure silver, but Ag/CdO reveals additional mass loss during the first cycle. It is known that CdO decomposes into Cd and O2 at 1360 °C (see the inset of figure 3), SnO2 at 2373 °C and ZnO at 2160 °C [27]. As the boiling and vaporizing temperature of Cd is 767 °C, free atoms of Cd can evaporate from the surface of the contact material [27]. As this process does not occur in SnO2 and ZnO, it leads to the accumulation of these oxides on the surface of the CM.

Unlike Ag–oxide systems, the major changes in Ag/C are registered in the low temperature range up to 1000 °C (see figure 4(f)). We see that before silver melts the Ag/C CM loses 3% of its mass, and when Ag starts melting an additional 2% is lost. Since there is no loss of silver in this temperature range we attribute the mass loss to the complete burning of carbon from the sample. The absence of any detectable mass loss during the second thermal cycle supports this scenario.

3.1.5. Wettability. For each sample we measured the corresponding adhesion work in interaction with liquids. The WEs were constructed following the Fowkes procedure as described in section 2. The obtained WEs for our samples are presented in figure 5. This variable is of particular importance since it determines if a liquid can wet a solid surface or not, and as stated earlier all liquids whose components of the surface tension fall below the WE have a high tendency to wet the solid surface. One can see that the surface area below the WE for the Ag/CdO sample is smaller than for other alloys used in this study. Very similar behaviour is observed for Ag/C, followed by Ag/SnO2 and Ag/ZnO. At the other end the largest surface below the WE was observed for the Ag/WC and Ag/WC–C samples.

The interaction of an alloy surface and liquids is of particular importance for the stability of the contact material.
4. Discussion

In the previous experimental sections, we have seen that the natures of the inclusions as well as their morphology and distribution in the silver matrix determine the properties of its form. The more a composite is hydrophilic the more the surface is exposed to corrosive interactions. It can thus be concluded that Ag/CdO, Ag/C, Ag/SnO2 CMs have better protection against aggressive environments, thus ensuring stable contact resistance.

3.1.6. Temperature dependent resistivity and thermal conductivity. To further examine the role of inclusions, we measured the electrical resistivity of the samples in the 4.2–300 K temperature range. Measurements at low temperature are of particular importance as most of the phonon modes are frozen out, thus allowing one to see how inclusions or structural defects contribute to the scattering of conduction electrons. In figure 6 we present the resistivity as a function of temperature for all samples of this study. All curves reveal a metallic temperature dependence (d\(\rho\)/dT \(<0\)) similar to pure silver [28]. The good metallic behaviour results from the existence of silver percolation paths as seen before. However, inclusions increase the absolute value of the resistivity. At the microscopic level this means that the mean free path of the electrons is shorter. Our data further show that the room temperature resistivity of the CMs could rise even by a factor of 4 with respect to the value of the pure silver [28]. For the sake of comparison the absolute values of the room temperature resistivity and the ratio with respect to the International Annealed Copper Standard (IACS) are presented in table 1, and compared with the literature value of pure silver \(\kappa_{\text{el}}\) of silver based CMs can be estimated from the Wiedemann–Franz law [30] \(\kappa_{\text{el}} = LT\sigma\), where \(L\) is the Lorentz number and \(\sigma\) is the electrical conductivity.

\[
\kappa_{\text{el}} = \frac{L}{\Omega_{1} \rho_{(290 \text{ K})}}\times 10^{31} \text{ W m K}^{-2}
\]

In pure silver, at \(429 \text{ W m K}^{-1}\). It is obvious that the \(\kappa_{\text{el}}\) of all samples is reduced with respect to that of the bulk silver, but the order of magnitude remains the same. The contribution to thermal conductivity which comes from phonons in the CMs cannot be higher than that of bulk silver, thus we conclude that electronic contribution dominates thermal conductivity in these CMs as well.

3.2. Performance characteristics of contact materials

All materials used in this study were subjected to switching operation tests according to the procedure described in the previous section. The results are summarized in table 1. We first see that Ag/Ni, Ag/WC and Ag/WC–C samples show unenviable characteristics with 47% and 9% of welding or sticking events. Therefore, they can be ruled out as contact materials for the present application. Other alloys such as Ag/C, Ag/ZnO, Ag/SnO2 and Ag/CdO show better performance with regard to sticking and welding. In this set of samples, Ag/CdO was the only sample for which a sticking event was recorded. It is important to emphasize here that for the operation of contact materials in real situations other parameters like stability of contact resistance and low temperature rise under nominal current are also of great importance. They are thus listed in table 1. We note a remarkable resistance stability of Ag/CdO and Ag/C alloys. Indeed, for these two samples resistivity deviates by only 22% and 34% respectively, while in others it exceeds 80%. Finally, we see that the temperature rise in \(\Delta T = 52 \text{ K}\) is smallest for the Ag/C alloy, resulting from its remarkably low contact resistance. For the others this increase is around 80 K, which is still below 100 K, the limit imposed by the IEC standard. From these results Ag/C seems to be the best candidate; however, one major drawback was noted. Although the erosion rate is acceptable, the re-strikes that occurred indicate that the dielectric strength between open contacts was lowered.
One sees that the contact resistance varies with applied load to the interface between two contact materials. Indeed, Ag/CdO and Ag/Ni show a temperature rise $\sim$ (figure 6 and table 1). Since it does not depend on the material by the relation \[ R_c = \frac{\sqrt{\mu \rho}}{\pi H^2}, \] where $\rho$ is the resistivity of a contact material, $\mu$ a coefficient ($\nu = 1$ for clean surfaces), $H$ is the hardness and $F$ is the applied load to the interface between two contact materials. One sees that the contact resistance varies with $\sqrt{H}$ and $1/\sqrt{F}$. High $H$ gives rise to a small effective contact surface and influences the increase in $R_c$ accordingly. Large $F$ leads to a large contact surface and implies the flattening of the contact materials [32]. However, a high load provokes a fast deterioration of the contacts.

Our hardness measurements on soft annealed materials (table 1) show variations from one sample to another and figure 7 reveals a correlation between hardness and temperature elevation. The difference in hardness between the softest and hardest samples used in this study is a factor of 3. This suggests that for Ag/C one can apply a force three times less than for Ag/SnO$_2$ and increase the mechanical durability of the circuit breaker accordingly. The smaller force gives the possibility of increasing the nominal current without changing the Joule heating power.

In the first regime where the two contacts are closed and the nominal current is constant, the most important requirement is that the total resistance of the system is low. This guarantees the lowest Joule heat production and a temperature rise of the contact lower than 100 K, as required by the IEC 60077 standards. The total resistance is composed of the material resistance itself in series with the contact resistance of the interface. The material resistivity does not seem to play an important role in this situation. All samples show $\rho$ in the range of a few $\mu\Omega\,\text{cm}$ (table 1) and the temperature rise is also similar (table 1). Indeed, Ag/CdO and Ag/Ni show a temperature rise of $\sim 80^\circ\text{C}$, although the room temperature resistivity of the Ag/Ni composite is more than twice as high as that of Ag/CdO (figure 6 and table 1). Since it does not depend on the material resistance, the temperature increase most likely comes from the contact resistance. Generally, the conductivity between two contact materials depends on the contact surface. At a given pressure, defined by the contact device, a soft material generates a larger contact area than a hard one, as it is shown by the relation [32]:

\[ R_c = \frac{\sqrt{\nu \pi H}}{4F}, \] where $\nu$ is the coefficient of contact material, $\nu$ a coefficient ($\nu = 1$ for clean surfaces), $H$ is the hardness and $F$ is the applied load to the interface between two contact materials. One sees that the contact resistance varies with $\sqrt{H}$ and $1/\sqrt{F}$. High $H$ gives rise to a small effective contact surface and influences the increase in $R_c$ accordingly. Large $F$ leads to a large contact surface and implies the flattening of the contact materials [32]. However, a high load provokes a fast deterioration of the contacts.

In addition to the large variation of contact resistance ascribed to hardness, the temperature rise of contact materials is also very sensitive to the chemical stability of the surface. Although it is well known that silver is remarkably stable regarding its resistance to oxidation, do the various inclusions alter its chemical stability? No direct measurements are made under the conditions of use but it is well established that the resistance of a material to corrosion or oxidation is directly linked to its ability to repel liquids [33, 34]. Our wetting experiments on the various composites have shown that Ag/CdO, Ag/C and Ag/SnO$_2$, the best performing materials, have a small WE meaning that they are hard to wet. This strong liquid repellency probably plays a crucial role in avoiding sticking and welding as we will discuss further, but it also protects the material against corrosion and oxidation, which is essential to ensure the time duration of the device working sometimes in a very aggressive environment (saturated humidity, salty, high temperature).

Under a fast current rise, a few milliseconds are required before the mechanical opening of the contact. During that time, the current might be an order of magnitude, possibly $\text{di/dt} = 36\,\text{kA ms}^{-1}$, higher that the nominal load. The major issue in this critical regime is to avoid any sticking or welding that would make the opening slower or impossible, and thus dramatically increase the amount of energy to be dissipated. Sticking or welding events result from a local melting of the silver due to the Joule heating and arc heat. Melting increases the contact area by spreading the Ag–liquid at the interface reducing the contact resistance. A fast drop of the temperature follows, possibly below the melting temperature of silver, resulting in the welding of the interface. Many parameters may prevent this from happening. So far we have shown that resistivity does not change significantly from one CM to another. The hardness and local pressure at the interface do not play a major role either. Could the different heat conductivity and chemistry at the surface be the main origin in different sticking and welding behaviour?
deviation of contact resistance in these contact materials is 88% and 100%, respectively.

In addition to the CMs containing oxides, it is most likely that Ag/C owes its performances to the solid lubricant behaviours of graphite (strong liquid repellent). This material is now used in protective switching devices where strong anti-welding properties are required. However, a severe drawback prohibits its use in dc high-speed circuit breakers. It was found that during the operation the presence of carbon provokes re-arc ing between the contacts.

5. Conclusion

To conclude, this study shows the relation between material characteristics such as resistivity, hardness, surface morphology, thermodynamics and wettability on one side and switching performance of dc circuit breakers using these CMs on the other. We showed that in order to understand the functionality of the contact materials a relationship between these characteristics must be established. Resistivity of a few $\mu \Omega \text{cm}$ and hardness of a few tens HV are required. Composite materials which are difficult to wet by liquids are also desirable. Finally, in Ag/oxide composite materials it is important to have an oxide which decomposes during the arc formation to prevent the formation of large oxide areas on the top surface of the contact materials and to help in heat dissipation.

Acknowledgments

This work was supported by the Swiss National Science Foundation through the NCCR Transfer Project, Grant No 51NF40-144632 and by Secheron SA. The authors thank Alberto Ubaldini from the University of Geneva and Volker Behrens from Doduco GmbH for fruitful discussions. We thank Chris Nazeri from Secheron SA for a critical reading of the manuscript, and Ecarla Fanny from CSM instruments for performing the nanoindentation experiment.

References

[7] Zoz H, Ren H and Spath N 1999 Improved Ag–SnO$_2$ electrical contact material produced by mechanical alloying Metallurg. 53 423

Figure 8. Number of sticking (black symbols) or welding (red symbols) events normalized by the number of tests versus the thermal conductivity of the materials derived from the electrical conductivity measurements.


[17] Vinaricky E and Behrens V Switching behaviour of silver/graphite contact material in different atmospheres with regard to contact erosion Proc. 44th IEEE Holm Conf. on Electrical Contacts (Arlington, VA. 1998)


[21] Zhenbiao L, Lichun C and Guansheng Z 1996 A review on theoretical investigation of electrical contact materials Proc. 42nd IEEE Holm Conf. and 18th Int. Conf. on Electrical Contacts (Chicago, IL, 1996) p 488


[26] www.metalor.com/em/electrotechnics/Products/Silver-alloys


[29] Vinaricky E et al 2010 Data Book of Electrical Contacts ed G Woerle (Muehlacker: Steiglitz Verlag)


