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Non-Linear Behavior of a Metallic Foam for the Reduction of Energy Losses at Electrical Contacts in the Aluminum Industry

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Abstract

Electrical contacts are found at many positions in an aluminum plant. Transformers, rectifiers, breakers, shunts, busbars connections, risers on the electrolysis cell and collector bars to the busbars are all electrical interfaces that show electrical contact resistances. The use of a specific metallic foam suppresses more than 80% of the electrical resistance. Measurements on Cu/Al and Al/Al contacts are presented. Non-linear effects such as the decrease of the electrical resistance with the increase of the current density and temperature are discussed. The impact of the pressure between the plates is also discussed.

Introduction

Energy is an increasing cost for the industry and all possible savings are welcome. This paper presents a new solution to the reduction, in fact almost suppression, of electrical contact resistance. Electrical contact resistance take place at all bolted interfaces. For instance, they can be found at transformers, rectifiers, as well as at external busbars bolted connections of the electrolysis cells. The electrical contact leads to an increase of the temperature due to Joule heat and can even degrade the contact over time. It is common to machine or clean the contacts or to use contact grease to avoid oxidation. However, no surface is absolutely flat and the electrical contact does never take place over the full surface. Moreover, aluminum and copper surfaces are always covered by a thin layer of oxide. The oxide layer is a very poor electrical conductor and lead to an electrical contact resistance. The concepts and the realization of a new material that suppresses the electrical contact are presented as well as a number of specific applications and measurements. The problematic of electrical contact is known since long. A good summary is given in reference 1. It is also well-known that "different metals have a place in this electrochemical series and the aim when building any metal structure is to try and ensure that metals that are in intimate contact with each other are similar in terms of their electrical potential. Here are some examples of the electrochemical potential for some commonly used metals" (2):

Zinc	= -1.11V
Aluminium	= -0.86V
Steel	= -0.68V
Stainless steel	= -0.61V
Copper	= -0.43V

Today copper is often replaced by aluminum in electrical circuits due to its lower cost and good physical properties. Joining aluminum to copper is typically very critical (3).

Ecocontact® foam

In order to improve the electrical contact, a metallic foam called Ecocontact® was developed with the target of creating a gas and liquid tight interface between the two bolted sections as well as creating as many as possible electrical connections between the two connected surfaces. The foam is composed of multi metallic low electrical resistance material such as copper, tin, silver which includes much harder material such as nickel. The hard material is aimed at penetrating through the oxide layer. The metallic foam is protected by a number of patents (4). Figure 1 shows a small piece of metallic foam magnified 10^5 times.

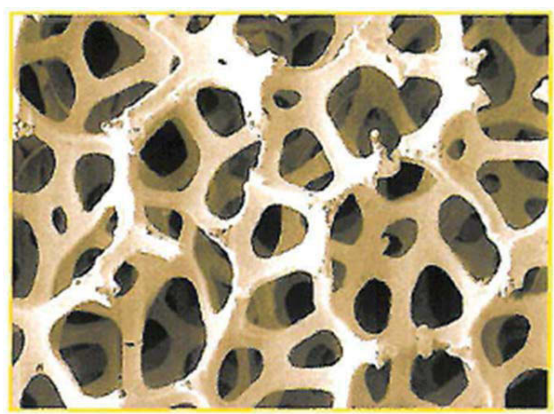

Figure 1: Metallic foam (Magnitude 10^5)

The foam appears as a porous material when magnified 100'000 times but it is not the case. The initial thickness of the foam plate is 1.6 mm. When used in between electrical conductors, the applied pressure reduces the thickness to 0.2 mm and makes it a perfectly tight material to liquids and gas. In order to test the behavior of the material towards liquid and gas, the ISO standard CEI 68.2.30 and CEI 68.2.11 was applied to samples. The first standard consists in creating two cycles at 55°C with à humidity of 95%, the second standard consists in generating a salt mist. Figure 2 shows the setup that was used for the test.

Figure 2: Salt mist and humidity to test the metallic foam

Figure 3 shows that neither of the test had any effect on the electrical contact for any of the five samples. The voltage remains 0.5 mV for all cases. The test simulates 20 years of use in normal atmosphere.

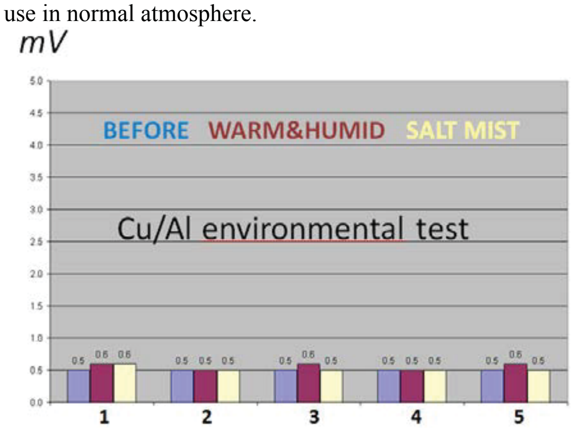

Figure 3: Five samples, before and after both tests

The development of the foam was done in such a way as to realize as many as possible electrical contacts between the two bolted connections. This was achieved by using some hard species able to penetrate the oxide layer and finally access the metal parts being copper and/or aluminum. As the foam is based on silver, the electrochemical potential is very low and resulting electrical resistance is most of the time less than 1 mV.

Figure 4 shows that the needed pressure is about one third of what is normally used in electrical contacts.

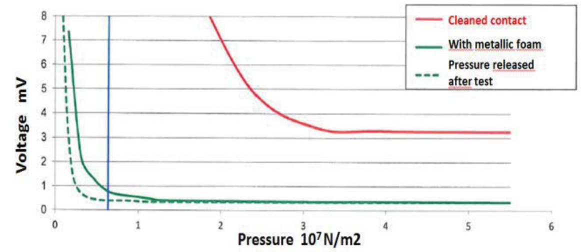

Figure 4: Voltage as function of pressure

The lowest voltage that could be achieved by this perfectly clean contact was 3 mV and this for any type of pressure. In the same time, the voltage was reduced by a factor 10 when using the metallic foam. This was achieved with a pressure that is approximately 3 times lower. It is also interesting to notice that the voltage remains low when the pressure is released down to less than 0.5 10^7 N/m2. This can be explained by the foam flexibility that returns to about 0.8 mm if completely released. The electrical connections remain active. Figure 5 illustrates the concept of electrical connection between the two conductors.

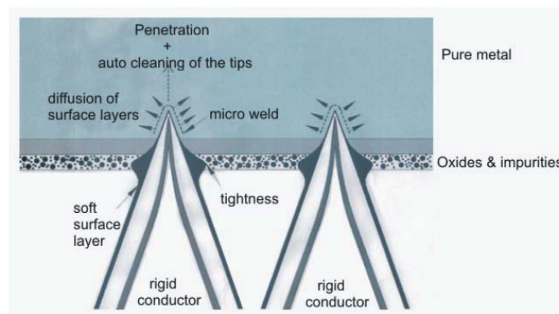

Figure 5: Metallic foam performance principle

The rigid structures in the foam cross through the oxide layer and penetrate the metal. Micro-welding of the tips allow for the diffusion of the surface layers. The surface layer is soft and generates a tightness joint which prevents further oxidation and any alteration from the external environment. As a result the achieved electrical contact is fully stable over time.

As the number of tips is very large, the electrical resistance is very low. This is further illustrated in figure 6 showing how the module of the electrical field is behaving in a contact where there are insulated areas of 30 micro-meters (black areas) in length. The current must flow around the insulated areas and the electrical field is much higher at the edge of the insulated areas. This leads to the well-known “fringe” effect, in other words to an increased voltage or electrical resistance.

1 A/mm2 was applied at the upper surface

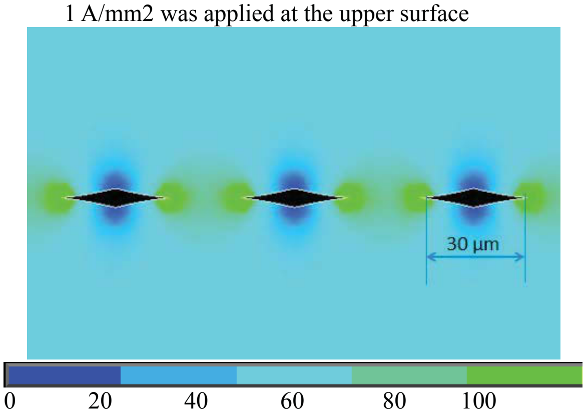

Figure 6: Module of electrical field (V/m)

The metallic foam is filling the insulating gaps and creates hundreds of electrical contacts suppressing the over-voltage as shown in figure 7.

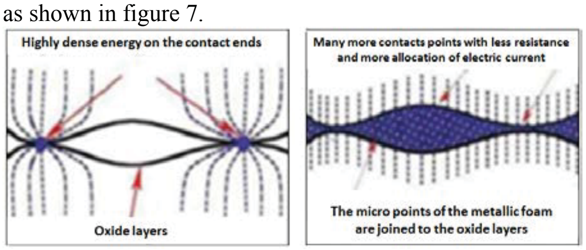

Figure 7: Metallic foam performance principle

An interesting behavior of the metallic foam is that the increase of temperature, or in other words the increase of agitation at microscopic level, helps at creating more electrical contacts between the two conductors. As a result, the contact voltage is decreasing when the temperature is increasing. This is a remarkable property that is normally opposite for all types of electrical contacts. To demonstrate this property the following experience is performed:

On a 10 cm X 10 cm copper to copper bolted connection, a current of 1000 A is imposed. The voltage is measured before and after the implementation of the metallic foam. A torque of 7kgm is imposed for both cases. Figure 8 shows the setup and where the voltage was measured. Figure 9 shows the implementation of the metallic foam.

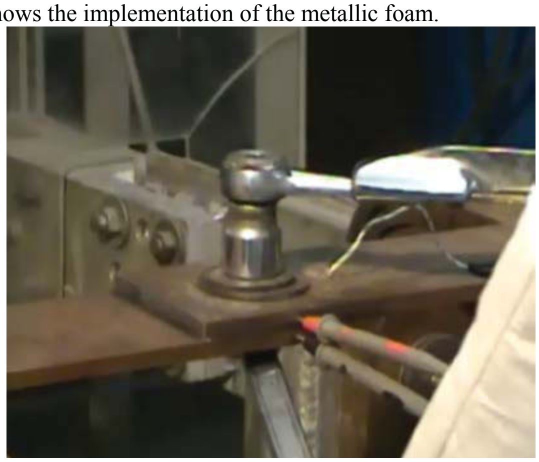

Figure 8: 10X10 cm, Cu/Cu contact

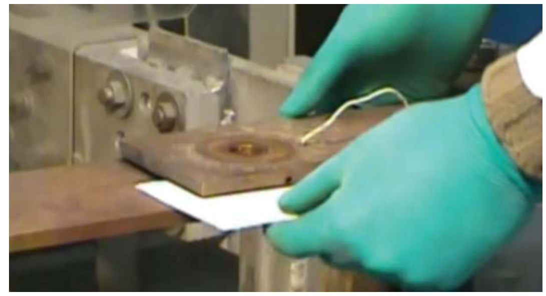

Figure 9: Implementation of the metallic foam

After some times, the current is increased from 1000 A to 10'000 A. As a result, the conductor is heating up and the contact is heated by thermal conduction. When the temperature reaches 220 °C, the current is reduced to 1000 A before cooling drastically by pouring cold water on the contact as shown in figure 10.

Figure 10: Water cooling on the contact

Figure 11 shows the temperature and contact voltage as function of time. Five periods can be observed:

1) The current is at 1000 A and the contact is between copper to copper without any special treatment. The contact voltage is 140 mV.
2) The metallic foam is inserted and the current is kept at 1000 A. This represents a current density of 10 A/cm2 in the contact. The contact voltage decreases to 3.6 mV
3) The current is increased to 10000 A, the conductors are overheated. The contact voltage jumps to 39 mV. This is about proportional to the current increase. While the temperature is increasing, the contact voltage is decreasing. When the temperature reaches 220°C, the voltage is down to 9 mV.
4) The current is decreased to 1000 A. The contact voltage is now 0.8 mV. Obviously the increase of temperature increased the number of electrical contacts between the two conductors.
5) The contact is quickly cooled to room temperature by pouring cold water on the conductors. The contact voltage is not affected and remains at 0.8 mV.

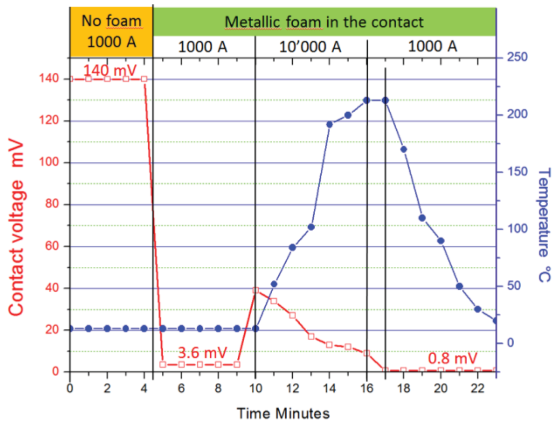

Figure 11: Contact voltage versus current and temperature

Applications

Copper-aluminum plate

The first application concerns the electrical contact measured between a copper "diamond" silver-welded on an aluminum beam of an electrolysis cell. Figure 12 shows the beam and the copper plate used to accommodate the copper rods of the anodes.

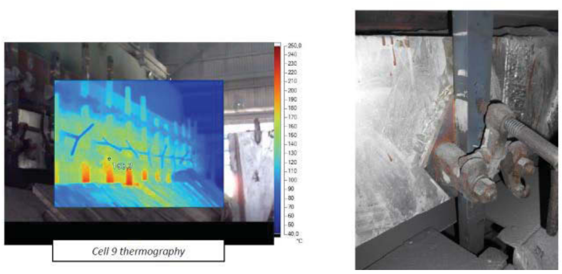

Figure 12: Thermography of beam "diamond contact"

The thermography suggests that the contact resistance between the copper plate and the beam is rather high. In fact the voltage varies from 10 mV to close to 200 mV in the worst case. Figure 13 shows where the voltage was measured.

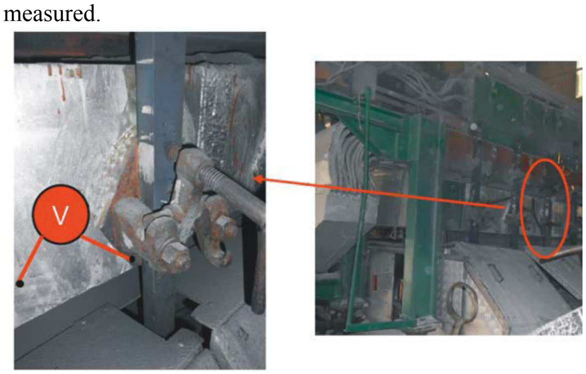

Figure 13: Cu-Al Voltage measurement

Figure 14 shows the metallic foam that was implemented in between the aluminum beam and the copper plate.

Figure 14: Implementation of the metallic foam

The decrease in voltage is total and leads to less than 1 mV. In fact the result does not depend on the initial voltage and always leads to a voltage that is lower than 1 mV (Figure 15). The current after implementation was lower. This has nothing to do with the contact but depends on the anode setting.

Measurement point	Before using metallic foam	After using metallic foam				Gain
		Beginning	After 1 H	After 24 H	Normalized	
A	168 mV	0,8 mV	0,7 mV	0,7 mV	0,8 mV	99%
Anode internal current intensity	2,13 kA	1,8 kA (due to anode level modification)				

Figure 15: Voltage reduction for Cu-Al contact

In order to minimize the implementation cost, a study was performed on the origin of the over-voltage. Figure 16 shows how the current is flowing in the copper plate. Most of the current is flowing in the lower part of the plate.

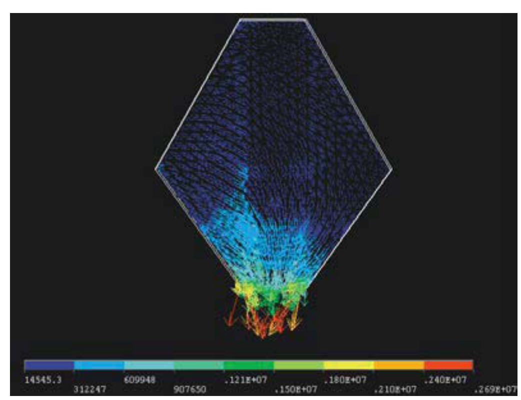

Figure 16: Current density in the copper plate (A/m2)

Finally figure 17 shows the area that can be cured with the metallic foam to save more than 95% of the contact voltage. The impact of reducing the surface of the metallic foam to the lower part only is an increase in the voltage of less than 1 mV. This shows the importance to understand where the current is flowing.

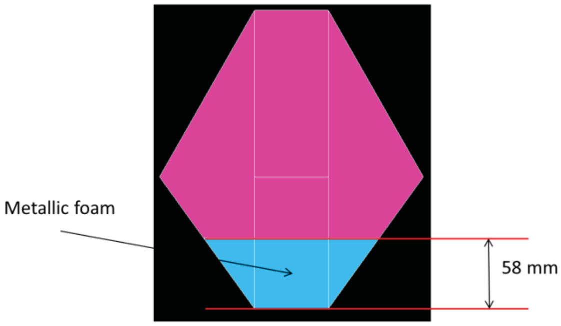

Figure 17: Minimization of contact area

The potential energy saving for this application is easy to determine. The average voltage is close to 30 mV, the average current is 80 kA and the number of cells is 2200. This represents 2.4 kW per cell or 46 GWh/year.

High voltage Transformer

Another example comes from an ERDF 75 MW transformer where energy can be saved. The situation was becoming critical on one transformer due to the high temperature that was found at the connections of the transformer. Figure 18 shows the transformer and the over-heated connections.

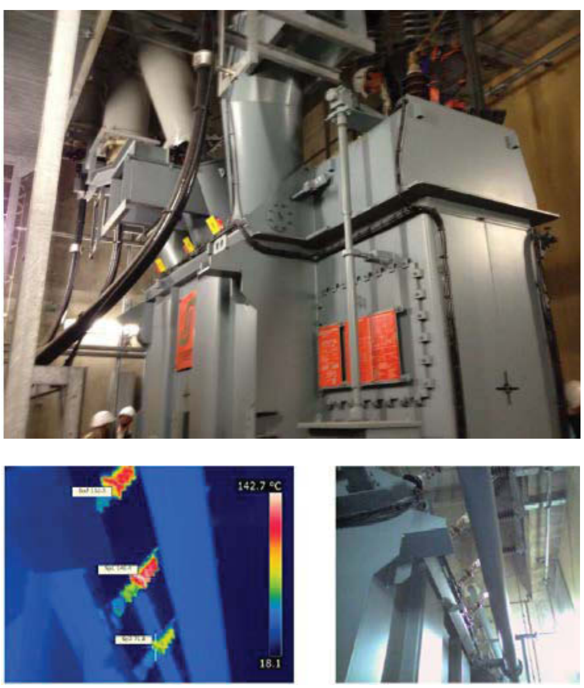

Figure 18: High Voltage Transformer

The highest temperature was measured as 140°C. This is critical as a further temperature increase could lead to the destruction of the connection. The high voltage wires were analyzed and the metallic foam placed at the three bolted connections as shown in figure 19.

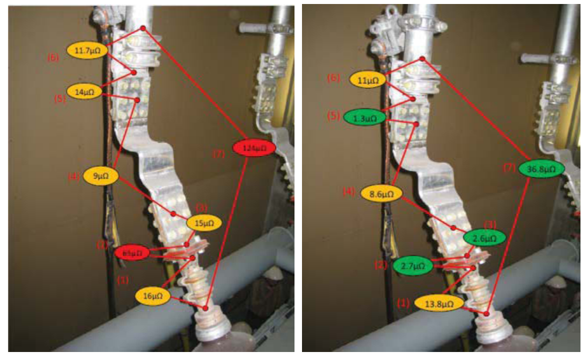
Figure 19: Electrical resistance before (left) and after (right) insertion of the metallic foam

The electrical resistance along the conductor is shown before and after insertion of the metallic foam. The foam was inserted on the three bolted plates. The resistance decreased by more than 90%. As a result, the temperature was decreased to about 80°C which correspond to the transformer temperature. The electrical resistance is also slightly decreased in between the bolted contacts due to the reduction of the temperature. In this example the reliability of the installation was the most important aspect, however, 5 GWH/year are saved. The intervention only took less than 1 hour.

Aluminum-aluminum bolted busbars

The last type of interface that we want to highlight is an aluminum-aluminum bolted interface which is often found in aluminum smelters. Figure 20 shows horizontal bolted contacts between aluminum busbars.

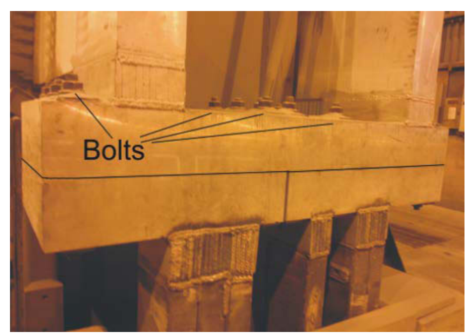

Figure 20: Al/Al bolted busbars

A number of such contacts were measured. Table 1 presents the typical value for different currents.

Table 1: Al/Al voltage and temperature

Current	Before		After implementaion of the metallic foam on 30% of the surface	
kA	mV	°C	mV	°C
40	53	120	2	107
40	54	140	3	117
60	42	131	6	100

The table speaks by itself. The efficiency of the metallic foam is more than 80% with only 30% of the surface covered with it.

Conclusions

The metallic foam has demonstrated new interesting features such as:

- The lowest contact electrical resistance at any torque
  - Without cleaning
  - Without machining
  - Without surface treatment
- Energy saving
  - Minimum 80% reduction of contact losses
- Contact lifetime, stability and reliability improvement
  - Tight to tough environments
  - Reduction of maintenance survey
  - Lower temperature for same current intensity
  - Capacity to take overloads

Acknowledgement

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