Inside the Aluminum Contact Spot

Magne Runde
SINTEF Energy Research
Trondheim, Norway
magne.runde@sintef.no

***Abstract*—The electrical properties of a power connector – such as the resistance during its service life – depend on the number, size and quality of the tiny contact spots ("a-spots") where the current crosses the contact interface. Contact degradation or aging are due to processes occurring in and near the contact spots. The current density may here become very high. Careful scanning electron microscopy investigations of contact spots from idealized and heavily stressed aluminum contacts that have carried DC show that the electron flow was accompanied by a mass flow by electromigration. This led to a gradual mass depletion in the cathode, resulting in poorer electrical conductivity and aging. When AC was passed in similar contacts, the high voltage drop caused a local 100 Hz thermal cycling of the contact spots. Subsequent electron microscopy examinations of sectioned contact spots suggest that the associated thermal expansion and contraction caused thermal fatigue and cracking, impairing their current carrying ability.**

***Keywords*—contact spots, power connectors, aluminum, deterioration, electromigration, thermal fatigue**

I. INTRODUCTION

Their good electrical conductivity has caused copper and aluminum to become the preferred electric conductor materials for power circuits. When comparing the cost and performance of these materials in some detail, the differences are in several aspects surprisingly large. The electrical conductivity of copper is around 60% higher than aluminum. But electrical conductivity – when measured in Siemens per meter – is a "volumetric quantity". When also considering that copper is more than three times denser than aluminum, the latter material comes out far better. By using standard values for density and resistivity, it can easily be shown that when comparing electrical conductance per kilogram, aluminum is superior to copper; providing around 13.7 mS/kg of conductance, which is about twice that of copper. In other words, a copper conductor is twice as heavy as an aluminum conductor with the same resistance, and weight is important in many applications.

Then there is cost. Commodity prices for metals – including copper and aluminum – have always been fluctuating considerably. The tendency over the last 15 years is, however, that copper prices have increased more than aluminum prices. At present (Q1 of 2019) copper and aluminum sell for around USD 6000 and USD 2000 per metric ton, respectively. By using these numbers, the comparison can be extended to also include cost of electrical conductance. Then aluminum comes out even more favorable, with a value of around 7 mS/USD compared to copper's 1.1 mS/USD. Hence, they differ with a factor of around six. So, from a purely economic perspective, aluminum is the obvious choice for power conductors.

However, selecting a suitable conductor material is more than a matter of material cost alone. At the end of every conductor, there is an electric contact of some kind. When it comes to making inexpensive and reliable contacts, connectors, joints, splices, etc., there is a substantial difference between aluminum and copper. Copper is the easier one to deal with.

The difference in contacting properties is of course related to the physical properties of these metals. Mainly two properties are normally held up as causing difficulties with aluminum: i) the robust and electrically insulating oxide film always present on its surface, and ii) the high creep rate that over time gives mechanical relaxation and may reduce the contact pressure. (Copper also has surface films, but these are less problematic, and the creep rates for copper at relevant temperatures are lower.)

Thus, insight into these peculiarities of aluminum is required when designing contacting devices. In comparison, copper is more forgiving.

For larger conductor cross-sections it has proven not that difficult to make reliable aluminum connectors that show an excellent performance over decades. Typical examples are bolted bus bar joints, compression connectors on overhead power lines, and connectors for underground cables. For lower ratings – typically with conductors below 16 mm^2 – contacting aluminum becomes more difficult. This has far-reaching consequences, as aluminum is rarely used in residential wiring, in the automotive industry and in other applications employing smaller conductor cross-sections.

A better and more complete understanding of the aluminum contact interface and the mechanisms that may cause it to deteriorate over time, could make the connectors simpler and more reliable. Even more important, it could open for use of aluminum for smaller conductor cross sections, giving substantial cost savings.

Considering degradation of aluminum connectors, oxide films and creep may not be the only culprits. There may be other phenomena also contributing. This article reviews and discusses two other possible degradation mechanisms, namely electromigration and thermal fatigue. The aging of contact spots created in idealized aluminum contact interfaces is studied. The approach is to delve into "the microworld of the contact spot" [1] by means of scanning electron microscopy (SEM).

Initially, a few basic concepts from the general understanding of electric contact interfaces are briefly reviewed [2].

II. CONTACT INTERFACES AND CONTACT SPOTS

In general, only a small part of the apparent contact area carries the current from one conductor and over to the other, as illustrated by the schematic of a bus bar joint in Fig. 1.

Because no surfaces are perfectly plane, the bus bars touch each other only in a part of the apparent or nominal contact area. Moreover, even areas being in mechanical contact do not necessarily conduct current. Oxides or other insulating surface

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

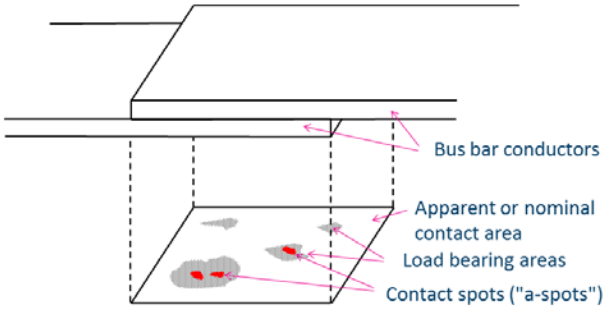

Fig. 1. An electric contact interface (schematically).

layers may prevent that from happening. The areas of true metal-to-metal contact – often referred to as "a-spots" – only constitute a small fraction, maybe as little as a few per cents, of the interface.

The electrical properties – first and foremost the resistance during the joint's lifetime – depend on the number, size and quality of these tiny contact spots. To explore and understand the behavior of a contact, phenomena and processes occurring in and in the immediate vicinity of the contact spots are the most interesting ones.

III. Setup for Making Detectable Contact Spots

Just finding the contact spots is a major challenge. The setup and procedures used in the investigations reviewed here are outlined in Fig. 2 [3]–[5].

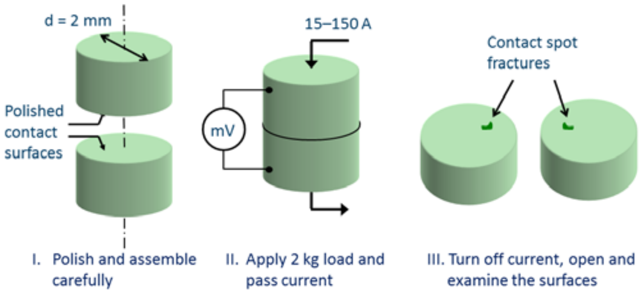

Fig. 2. Preparation of the idealized aluminum contacts used to study contact spots (somewhat simplified).

Tiny aluminum cylinders, only 2 mm in diameter, were used. The circular end surface of each cylinder was carefully polished, and the cylinders were then put carefully on top of each other, forming an aluminum-aluminum contact interface. Then – again with great care – a dead weight of 2 kg was applied to press them firmly together. The 20 N force yields a high contact pressure on the some 3 mm^2 large interface.

Current was then applied and gradually increased. Up to around 150 A was passed with a duration from a few minutes to several weeks. Then the current was turned off, the two contact members separated, and both sides of this contact interface were examined by SEM and in some cases also with an optical microscope.

In most cases just one contact spot was formed. When separating the two aluminum cylinders, the contact spot broke up and the resulting fracture could be seen on both sides/surfaces. The SEM image of Fig. 3 shows the circular top surface of one of the small aluminum cylinders. 85 A have passed, and all current went through the tiny white spot indicated. The current density in this area was formidable, around $2{\cdot}10^6$ A/cm^2. The rest of the interface did not pass any current.

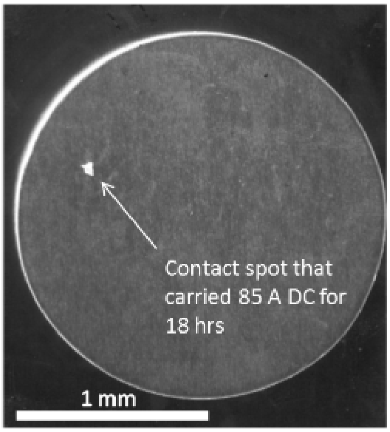

Fig. 3. Contact surface with the fracture of its only contact spot [3].

After the two cylinders were mated, there was in most cases no electrical connection between the two, even with the 20 N force applied. Voltage had to be raised to some 0.5–1 V before current suddenly started to flow. The electric field in the oxide film then became so high that the film broke down dielectrically. This phenomenon – in the literature referred to as fritting [2] – could be nicely observed in this very idealized setup. It is never seen in practical contacts, because the surface films there are ruptured mechanically.

Apparently, the contact spot was in these cases created at some arbitrary location, where this dielectric breakdown of the film occurred.

More than 100 experiments were carried out, both applying DC, AC and rectified AC. At full current, the voltage drops across the interface were in the range 80–300 mV$_{\text{peak}}$, corresponding to contact resistances of 1–5 mΩ. Hence, these contacts were heavily stressed. A voltage drop in the range of 100 mV is much. A good power connector should have a voltage drop at least one decade lower (i.e., some 10 mV) at rated load current.

The most important ability or quality of this setup is that it facilitates studying individual contact spots that have been subjected to known stresses. The amount of current that has passed a contact spot, for how long time, and to what voltage drop, are here known quantities. In addition, the bulk temperature of the aluminum cylinders was recorded. So instead of studying macroscopic contacting devices, this allows for investigating the core of the matter: namely the processes in and near the minute contact spots.

IV. DC Contact Spots

A. *Fracture Characteristics*

The contact spot fracture in Fig. 3 is shown to the left in Fig. 4, but at a higher magnification. To the right is the corresponding area on the opposite contact surface. The fractures of the two sides fit nicely together.

The tiny metallic junction constituting the contact spot never broke off in the contact plane when it had carried DC. It always fractured some distance inside the cathode, resulting in a characteristic protrusion or top on the anode side, and a

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

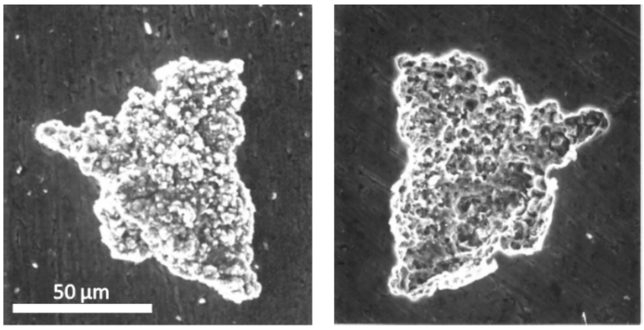

Fig. 4. Corresponding anode (left) and cathode (right) side fractures of a DC contact spot [3].

corresponding crater or hole on the cathode. This asymmetry is seen even better in Fig. 5 where the fractures from another DC contact spot are shown, but now from the side, nearly parallel to the contact surface.

There is a clear asymmetry here, even though both anode and cathode are pure aluminum, and temperature and voltage distributions near the a-spot are symmetric. Obviously, there must be a mechanical weakening inside the cathode member as DC contact spots consistently broke off inside the cathode.

B. *Size of Contact Spot Fractures*

The contact resistance R was measured just before the current was turned off, the resistivity ρ of aluminum is known, so the expected radius a of the contact spot – assuming one circular contact spot – can be calculated by means of the well-known equation

$$R = \frac{\rho}{2a} \tag{1}$$

For experiments where current was applied for less than an hour or so, the size of the fracture area corresponds well to this prediction, as shown in the example in Fig. 6.

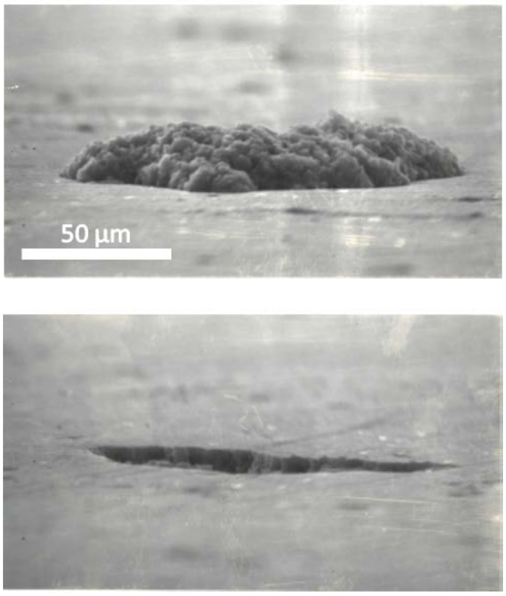

Fig. 5. Corresponding protrusion on anode side (top) and cathode side crater (bottom) of a DC contact spot, seen at a glancing angle with the contact surfaces [6].

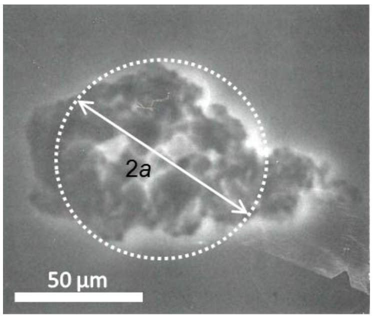

Fig. 6. Cathode side fractures of a DC contact spot with the contact spot area as predicted from theory indicated.

C. *Aged Contact Spots*

When current was passed for longer times, the fractures became larger than expected from the measured resistance, indicating that dynamic processes had been at work. Some kind of aging or degradation occurred as current was flowing.

Fig. 7 shows cathode side contact spot fractures from three contact interfaces where 40 A DC was passed for three days. The upper left one had two contact spots, the two others one each. By means of (1) the expected sizes of the contact spots were calculated, and these are indicated by the black circles. (The upper left $2a$ is determined by considering two equal resistances in parallel.

These contact spots are larger than predicted. Hence, their "quality" had degraded. When considering the voltage drops during the three days current was passed, a clear correlation emerges. The contact spots of the upper left images had a

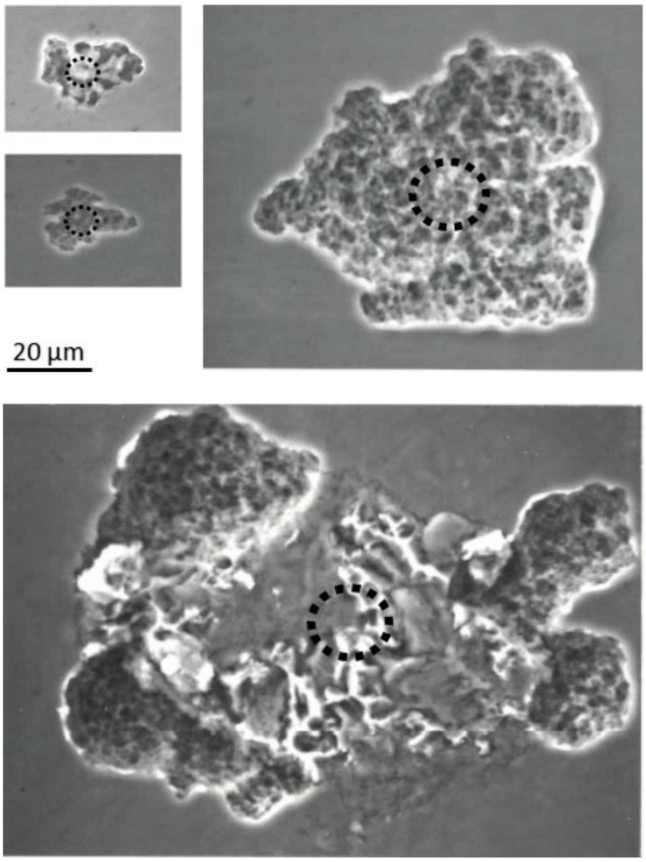

Fig. 7. Cathode side fractures of the contact spots of three interfaces [7]. The two smaller spots were in the same interface. The size of the a-spot areas as predicted from theory are indicated in each case.

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

rather stable voltage drop of 80 mV. The upper right was moderately unstable with a contact voltage in the range 120-150 mV for most of the time, and this resulted in a far larger contact spot fracture. The lower one, where the contact voltage was even higher and more unstable, typically between 150 and 200 mV and with brief fluctuations up to around 300 mV, resulted in an even greater fracture.

The local temperature rise in the contact spots is directly related to the voltage drop across the interface, and 300 mV corresponds to a contact spot temperature equal to the melting point of aluminum [2]. Hence, the spot in the lower part of Fig. 7 has probably suffered incidents of local melting.

Consequently, Fig. 7 shows essentially three stages of aluminum contact spot aging.

To study this degradation in more detail, contact spot fractures were cross-sectioned. This was done by immersing the aluminum cylinders in transparent epoxy resin, and after the epoxy solidified, the contact spot fractures were sectioned approximately through their center, perpendicular to the contact surface.

Fig. 8 shows micrographs from sectioning the anode side protrusion of a severely aged contact spot. The mid right image shows the contact spot fracture from above before sectioning. The area of this fracture is some 30 times larger than predicted from the resistance, as indicated with the black circle. The white line indicates where the fracture was sectioned.

These images clearly explain why the DC contact spots fracture inside the cathode. The metal some distance inside the cathode side has become porous. This clearly reduces the mechanical strength. When separating the contact members, the contact spot breaks up along these areas, not in the original interface. The opposite side of the interface (i.e., the anode), is solid and obviously stronger.

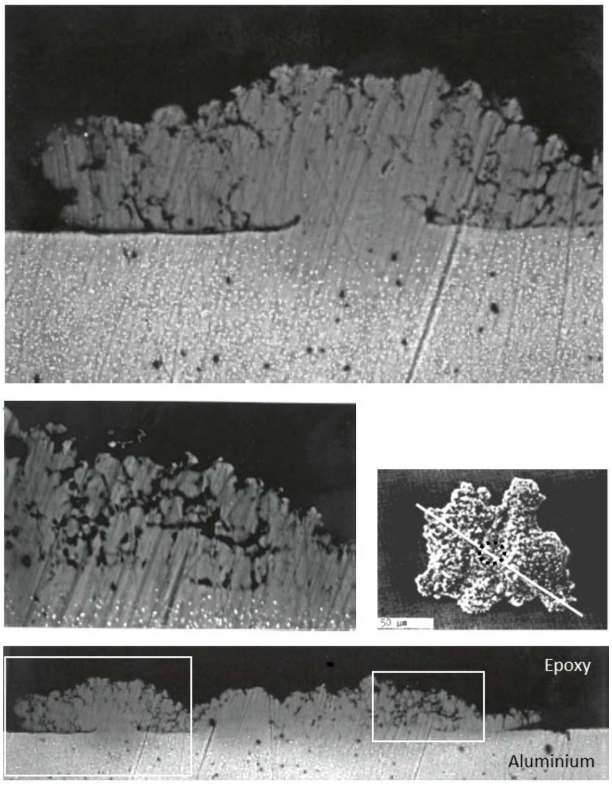

Fig. 8. Cross-sectioned fracture of the anode side of a deteriorated DC contact spot [6]. The lower image shows the entire depth profile, whereas the two upper ones are close-ups of the areas in the rectangles.

The reason for this weakening is that material has been transported across the interface, causing a mass depletion or deficit some distance inside the cathode. To map this mass flow, a little zinc was alloyed into the anode member. The zinc appears as white spots or precipitations in the SEM images. Evidently, the electron flow from cathode to anode has here been accompanied by a parallel mass or atomic flow in the same direction. This flow has caused a mass deficit inside the cathode, seen and pores, and apparently weakened the area mechanically, and – important in the context of electrical contacts – also reduced the electrical conductance substantially. The current had to find new paths as the original paths degraded. This is the reason for the larger contact spot fractures with some porous and worn-out areas and some fresher and more solid areas.

V. ELECTROMIGRATION IN CONTACT SPOTS

The process at work here is usually referred to as *electromigration*. It can be described as a current-induced solid-state diffusion process where an intense "electron wind" pushes the metal atoms in the same direction as the electrons. Electromigration occurs only under extremely high current densities and is a well-known phenomenon in large scale integrated circuits.

Even though the currents in the interconnects of integrated circuits are small, their minute cross-sectional area causes the current density to become high. Electromigration causes a mass flow that creates open circuit in the interconnects, and the thin film device fails. Mitigating electromigration failures has for decades been an important issue when designing such devices, and several books have been written on the subject.

Electromigration was first identified and proposed as a mechanism behind degradation and failure of bulk (not thin film) electrical contacts and connectors around 1985 [7]–[9]. Also in this context the most important parameter is the current density. The relationships between a contact spot's size, current, voltage drop, temperature, resistivity and so on, are known. By combining expressions from Holm [2] and Greenwood and Williamson [10], the average current density in a contact spot as a function of how much current the spot carries and to what voltage drop, can be derived analytically [9].

Fig. 9 shows this relationship in a log-log plot for three voltage drops. It turns out that the current density tends to be higher in small contact spots than in larger ones. Also included in the figure is the current densities found in thin film interconnects (up to around 10^6 A/cm^2) and in ordinary aluminum or copper conductors (up to 10^3–10^4 A/cm^2).

The contact spots of the experiments reported on here – typically passing around 100 A at 100 mV – fall in the upper right corner of Fig. 9, with current densities of around 10^7 A/cm^2. This is about ten times as high as in thin film interconnects. Contact spots carrying 1–10 A at a contact voltage of 10 mV – probably not unrealistic for a power connector – have a current density about as high, and higher than a thin film interconnect can handle without failing by

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

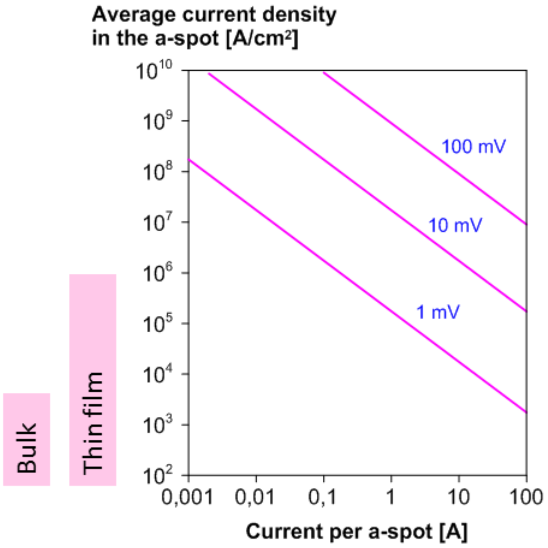

Fig. 9. Current density in contact spots for different voltage drops as calculated from contact theory, compared to current densities in bulk and thin film conductors [6]. Material properties are as for aluminum.

electromigration. Higher contact voltages and/or smaller contacts spots yield even far higher current densities.

However, the validity of this model for very small contact spots (i.e., leftmost part of the plot in Fig. 9) may be questionable. The contact spot size is here comparable with the mean free path of the electrons, so the contact theory at some point breaks down [11]. Still, these calculations support the hypothesis that electromigration also occurs in practical aluminum connectors and contacts.

VI. AC AND RECTIFIED AC CONTACT SPOTS

A. *Fracture Characteristics*

The contact spot fractures shown above are all from DC experiments. When AC was passed, the outcome – when considering voltage drops and size and appearance of the resulting contact spot fractures – was in part similar and in part quite different from the DC experiments.

Concerning the sizes of contact spots, these were as expected from the resistance only in the cases where AC current had been passed for a short time (minutes). The contact spot fracture sizes grew with time much in the same way as under DC, but the degradation – as signified by the size of fractured area – appeared to proceed more rapidly. Moreover, the voltage drop was in general higher and significantly more unstable under AC than under DC.

Fig. 10 shows a small and a much larger AC contact spot fracture. Their resistances when current was turned off were comparable, indicating that the "quality" of the lower one had degraded in the sense that current appeared to have found new paths. When separating, a larger fracture – almost 0.5 mm across – emerges.

The AC contact spots broke up in a more random manner, not systematically inside the cathode members as when DC had passed. The fracture of the upper image of Fig. 10 clearly extends both above and below the original interface.

Fig. 11 shows another example of a severely aged AC contact spot. Tops and craters are also here seen on both sides.

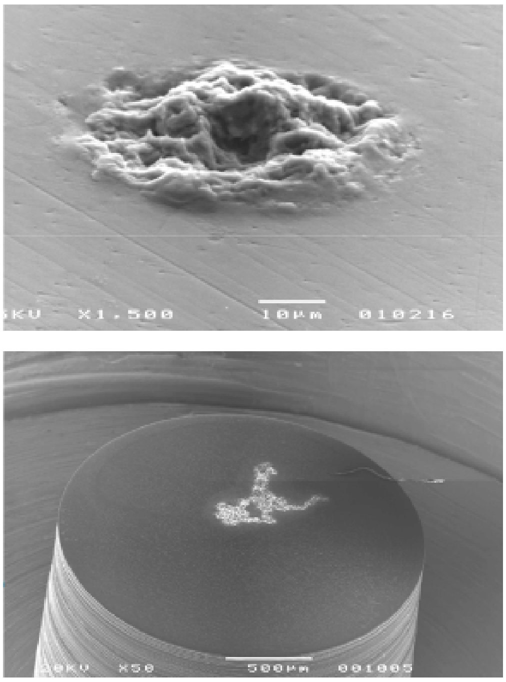

Fig. 10. Fractures of a fresh, un-aged contact spot, approximately 40 µm across (upper), and of a much larger and severaly aged contact (lower) [12]. Both carried AC

The fracture characteristics are assumed to be important, because they reveal the mechanically weakest areas. It is reasonable to assume that the same areas have had their current carrying ability impaired. A dense and solid region is both mechanically strong and conducts current well. Hence, contact spot aging manifests itself as areas with reduced mechanical strength.

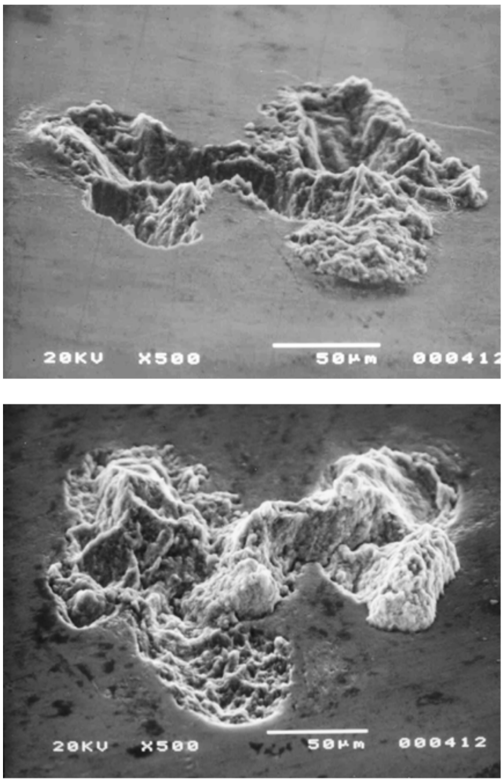

Fig. 11. Corresponding fractures of a severely aged AC contact spot [12].

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

Fig. 12 shows an AC contact spot fracture embedded in epoxy and sectioned. As can be seen, cracks extend deep underneath the contact spot and into the bulk of the aluminum. Similar cracks were also seen near the fracture of the opposite side. These clearly disrupt the current paths and can explain why the contact spot grew, much in the same manner as in the DC cases. However, there are also significant differences. The characteristic porous volumes seen inside the cathode part of aged DC contact spots – see e.g. Fig. 8 – were not observed near AC spot fractures. The mechanical weakening appeared to originate in, at least partly, formation of cracks and crevices, rather than a general mass depletion as under DC. Consequently, it is not obvious that electromigration is the dominating mechanism here.

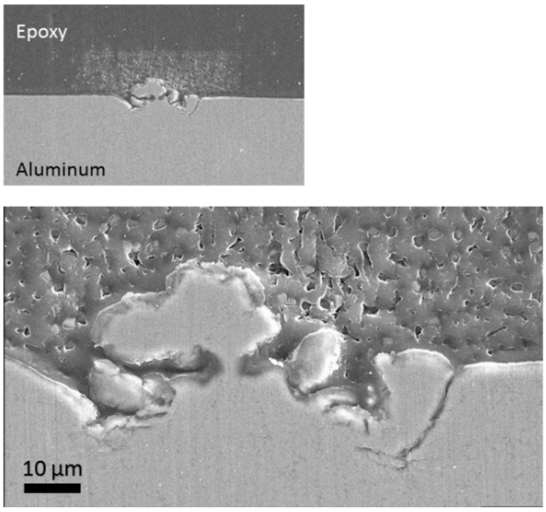

Fig. 12. Cross-section of one side of the fracture of a severely aged AC contact spot [12]. (The electron beam from the SEM has caused some heating damage of the epoxy resin.)

Even though electromigration is primarily associated with DC (or pulsed DC) conditions in integrated circuits, it may also occur under AC. The outcome in terms of mass redistribution is, however, harder to predict. Obviously, the same atoms are not simply jumping back and forth 50/60 times per second, without any net mass flow.

In order to look further into this, tests with rectified AC were also performed. Under such conditions, current flows in just one direction (as in DC) and the contact spots are at the same time subjected to the intense thermal stresses caused by AC. The temperature rise in the contact spots is directly related to the voltage drop, and the thermal time constants of the contact spots are so small that they heat up and cool down 100/120 times per second. With the high voltage drops seen in these experiments, this means a severe 100/120 Hz thermal cycling with a local heating up to several hundred degrees in and in the immediate vicinity of the contact spots.

The outcome of the rectified AC experiments was characterized by two things. First, these contacts were – when considering the voltage drop – far more unstable than the ordinary DC tests; and in this regard similar to the AC tests. Second, the contact spots in most cases fractured inside the cathode, as in the DC cases. Hence, passing rectified AC gave features from both pure AC and pure DC. SEM images showing both sides of a typical rectified AC contact spot fracture are presented in Fig. 13.

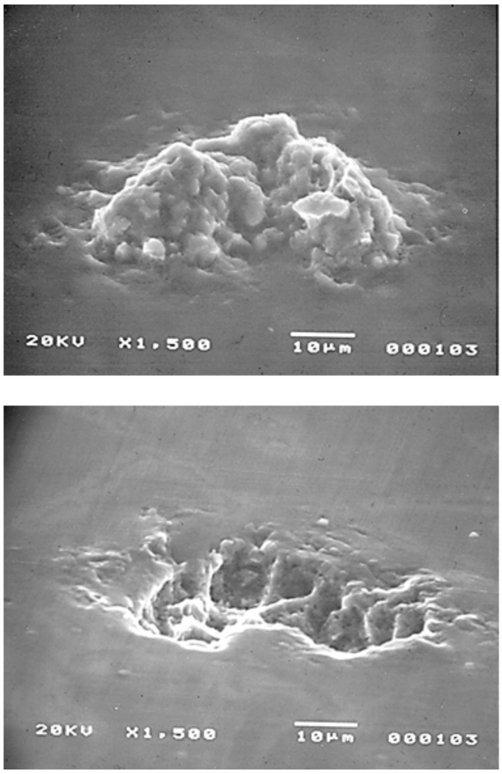

Fig. 13. Corresponding contact spot fractures from a contact spot that has passed rectified AC; anode (upper) and cathode (lower) sides [12].

Evidently, the 100 Hz heat cycling has an effect. It is reasonable to attribute this to the rapid thermal contraction and expansion of the metal in the contact spot and the mechanical stresses and strains this causes.

B. Recrystallisation and Thermal Fatigue

By means of metallographic etching techniques and polarized light, the grain distribution in polished metal surfaces can be visualized and observed optically. Depending on their orientation, the grains take a different color. Fig. 14 shows such polarized images of both sides of a DC contact spot fracture that has been sectioned. The aluminum grains are from a few tens to a few hundred micrometers across. Moreover – and this is the important observation – there is nothing particular with the grains in and near the contact spot. This area is – with regard to grain sizes – nothing different from the rest.

For AC and rectified AC contact spots which had been subjected to intense thermal cycling, this was not so. Fig. 15 shows the same type of images of two sectioned AC contact spot fractures. The magnification is higher than in the images of Fig. 14.

It appears that many small grains have been formed near the contact spots, whereas the areas further away are one larger grain. Such a recrystallisation may signify that the metal in this region has been subjected to mechanical strain and stress, and that it has been deformed and hardened. Lots of dislocations have been generated in the metal lattice.

It is speculated that this considerable difference in grain structure observed between the DC and AC contact spots can be attributed to the 100 Hz thermal cycling under AC. Repetitive, local compressive and tensile stresses in the contact spots lead to mechanical fatigue and cracking.

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

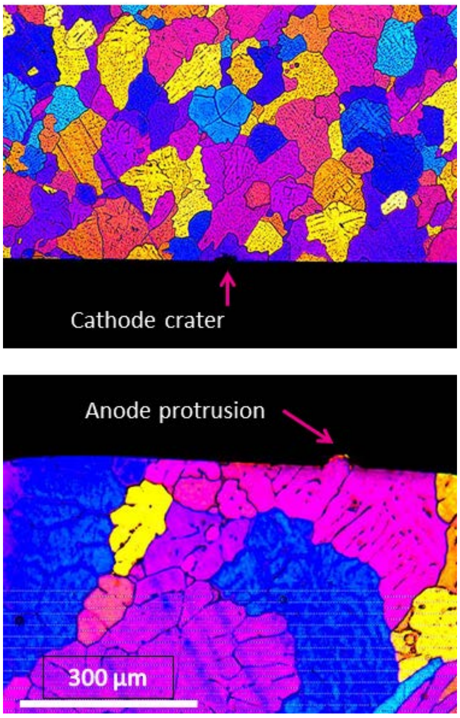

Fig. 14. Low magnification polarized light images showing the grain orientations as different colors in the aluminum cylinders constituting the contact members of a DC experiment [12]. The corresponding contact spot crater and protrusion are indicated by the arrows.

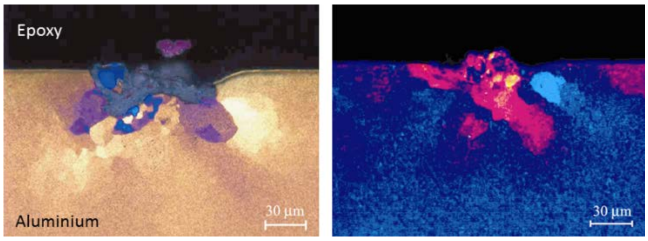

Fig. 15. Polarized light images of sectioned AC contact spot fractures showing the grain distribution near the contact spots [12].

Low stress cracking caused by cyclic thermal expansion and contraction is usually referred to as *thermal fatigue* and is known from various engineering disciplines [4]. Here, the cracks presumably interrupt current paths, forcing the current to establish new paths, thereby increasing the apparent contact spot size while maintaining a high contact resistance.

VII. DISCUSSION AND CONCLUSION

The crucial question is whether the phenomena considered here – electromigration and thermal fatigue – also occur in "real world" aluminum connectors. Or are these just some peculiarities that happen to take place under the somewhat unusual conditions of the contact interfaces studied here? This question cannot be answered with absolute certainty, but some comments and remarks may be appropriate and relevant.

Take electromigration first. Calculations suggest that the current densities in small contact spots become extreme, and much higher than in the interconnects of integrated circuits. The current density is an important parameter in this context, but it is not the only one. In addition, temperature and diffusion coefficients greatly influence the drift velocity. The conditions in a contact spot differ greatly from those of an integrated circuit, and results may not be easily transferable or applicable.

There have been failures in service in DC power contacts between aluminum and plated aluminum (i.e. asymmetric contacts), where the failure occurred only when current passed in one direction and not in the other. Hence, the current direction in an asymmetric DC connector was decisive for whether the resistance remained stable or not. It is hard to conceive other degradation mechanisms than electromigration that can explain this.

The thermal fatigue aging hypothesis is a more speculative one. It is also less relevant because it presupposes an intense thermal stress, with large temperature fluctuations in every power cycle. This translates into a high voltage drop. It can be argued that if a connector has such a high voltage drop, it is already failing. Consequently, thermal fatigue may only be a phenomenon occurring in the later stages of a contact degradation process. It is harder to envision that it initiates a connector problem.

As pointed out initially, a better understanding of the fundamental mechanisms and phenomena behind degradation of aluminum connectors could improve the existing solutions and also expand the use of this metal in power conductors. A few topics for future work – largely based on the findings reviewed here – are proposed in the following sections.

The resolution of SEM has in recent years improved greatly. For example, it is now possible to see 5 nm thick oxide layers on aluminum surfaces. Doing similar experiments as those described above but using state-of-the art SEM, may provide much more details about the microworld of the contact spot.

Another interesting task would be to do as they have been doing in thin films to reduce electromigration failures, namely alloy 1% of copper into the aluminum. Will this make an aluminum connector more stable?

Then there is modelling, both analytical and numerical. By assuming circular contact spots, it is possible to analytically determine electromigration drift velocities at every position in and near a contact spot under different currents, voltages, and temperatures. Accurately modelling the mass redistribution by electromigration would be an interesting task.

Finally, regarding the phenomenon of thermal fatigue: Will aluminum power connector reliability improve if they are made of alloys resistant to fatigue?

ACKNOWLEDGEMENT

Several collaborators and co-authors have contributed to the work and publications referred in this review. The most important ones are Elin Hodne, Helge Kongsjorden, John Kulsetås, Christopher Ruppert, Jarle Sletbak and Bård Tøtdal.

REFERENCES

[1] J. B. P. Williamson, "The microworld of the contact spot," in Proc. Holm Conf. Electrical Contacts, Chicago: Ill. Inst. of Technol., 1981, pp. 1-10.

[2] R. Holm, "Electric Contacts," New York: Springer, 1967.

[3] M. Runde, "Material Transport and Related Interfacial Phenomena in Stationary Aluminium Contacts," Doctoral Thesis, Norwegian Inst. of Technol., 1987.

[4] C. Ruppert, "Thermal Fatigue in Stationary Aluminium Contacts," Doctoral Thesis, Norwegian Univ. of Science and Technol., 2001.

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842

[5] M. Runde, H. Kongsjorden, J. Kulsetås, and B. Tøtdal, "Detection of a-spots in aluminum contacts," IEEE Trans. Components, Hybrids, Manuf. Technol., vol. 9, pp. 77-85, 1986.

[6] M. Runde, E. Hodne, and B. Tøtdal, "Current-induced aging of contact spots," Proc. 35th IEEE Holm Conf. Electrical Contacts, Chicago, 1989, pp. 213-220.

[7] M. Runde, E. Hodne, and B. Tøtdal, "Experimental study of the conducting spots in aluminum contact interfaces," IEEE Trans. Components, Hybrids, Manuf. Technol., vol. 13, pp. 1068-1073, 1990.

[8] J. Kulsetås and M. Runde, "Deterioration of aluminium contacts due to electromigration," Proc. 13th Conf. Electrical Contacts, Lausanne, 1986, pp. 118-122.

[9] M. Runde, "Mass transport in stationary contact points," IEEE Trans. Components, Hybrids, Manuf. Technol., vol. 10, pp. 89-99, 1987.

[10] J. A. Greenwood and J. B. P. Williamson, "Electrical conduction in solids, II. Theory of temperature-dependent conductors," Proc. Roy. Soc., vol. A246, pp. 13-31, 1958.

[11] R. S. Timsit, "Electrical conduction through small contact spots," IEEE Trans. Components, Packaging Technol., vol. 29, pp. 727-734, 2006.

[12] C. Ruppert and M. Runde, “Thermally induced mechanical degradation of contact spots in aluminum interfaces,” IEEE Trans. Components, Packaging. Technol., vol. 29, pp. 833-840, 2006.

This is the accepted version of a paper published in Proceedings of the sixty-fifth IEEE Holm Conference on Electrical Contacts 2019
http://dx.doi.org/10.1109/HOLM.2019.8923842