"WHISKERS" THE ROOT CAUSE OF SPONTANEOUS SHORT CIRCUITS

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Abstract

Silver whiskers, "could they be" the root cause of spontaneous short circuits? Silver whiskers are mainly found in Chemical plants, Oil refineries, Paper and Pulp industries, Sewage - and Waist water plants. All industries were a high amount of H_2S and SO_2 is produced. Silver is a metal that, when plated to copper, provides all the qualities required and does not reduce the conductivity. Silver is also resistant to many corrosive environments and its weak affinity to oxygen enables already thin layers preventing the increase of contact resistance. Silver plated copper therefore appears to provide all the advantages to the requirements of the electrical industry and hence it is widely used throughout.

However, silver does have a major disadvantage as well. It is prone to sulphidation and subsequently tarnishes. As most environments contain some concentrations of sulphur bearing compounds sulphidation is difficult to prevent in the long run. The result of sulphidation on silver is silver sulphide Ag_2S that is poorly conductive so causing complications like temperature rise on electrical contacts.

Moreover, from experience, this undesired compound has been also associated with a peculiar phenomenon. Under certain circumstances hair like crystals, commonly known as "whiskers", are grown virtually perpendicular from the silver plated surface. They prove to have silver content of more then 90 % and can reach lengths up to ten's of millimetres. Silver whiskers can result in spontaneous short circuits in electrical switchgear assemblies.

This paper sets out to highlight the problems, and dangers, of whisker growth and attempts to bring forward the reasons behind it and to identify methods of prevention. The root causes of silver whiskers, being the sulphur, the humidity in the ambient atmosphere and the temperature increase of the silver plated part (a hotspot) have to be investigated and be shared with you to reach the situation of eliminating the root cause of the possible spontaneous short circuit. It is stressed that the increase of permissible temperature rise for installed components, this due to application of modern insulation materials having a high withstand temperature, may contribute to a higher risk for the formation of whiskers in the future.

I INTRODUCTION

In the early 1970's, a serious problem occurred on one of the electro mechanical contactors in a low voltage switchgear assembly in Durban South Africa. By investigation of the contactor, strange fibres were found on the silver plated terminal flags.

During inspection of these fibres and tests carried out in the laboratory it was noticed that:

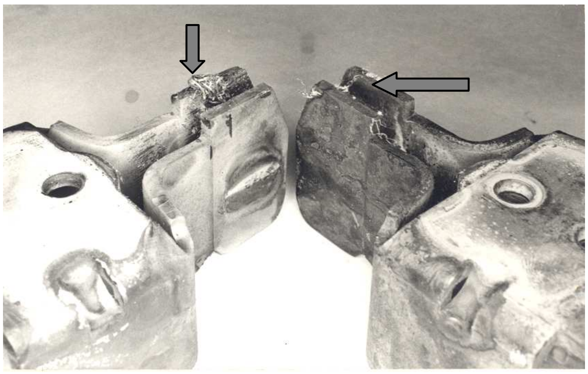
- the fibres were very good conductive,
- would turn into blank metal when heated up to 400 ^{o}C,
- that they became blank by cleaning them with "Thiomeum Hydrochloric" and
- that the blank fibres would fully resolve again in nitric acid: proving that the fibres were pure silver.

It was concluded in first instance that the fibres found were silver sulphide (Ag_2S) in combination with pure silver. Literature reviews lead to an article in ETZ of December 1962 written by Albert Keil and Carl-Ludwig Meyer [2&3]. In these papers, fibres were described as found on the contactor and were called silver whiskers. The circumstances described in the articles were very similar to the circumstances of Durban South Africa. Sulphur in the ambient atmosphere (the switchgear was installed in a switch house adjacent to a sulphur plant) and a high relative humidity of the ambient air were the case. First thought was that the high tropical temperature was the 3rd ingredient, but later it was noticed that the high ambient temperature was not the reason of growing these fibres but the temperature rise just originating from a contact subjected to ageing.

By studying the ETZ document it revealed that the phenomena was quite an old one and was experienced earlier in the U.S.A. and with other materials as silver as well. Such as cadmium, zinc and tin.

Nickel, chrome and gold seem not to be sensitive for whisker growth according these publications.

Mid 1974 another product failure appeared, this time on a refinery in the Caribbean's. During an investigation on switchgear installed the same type of fibres as found in Durban were detected.



Ambient circumstances on the Caribbean island were similar to the Durban refinery case that indicated again that silver whiskers were the cause. Above failures initiated a thorough literature survey as well several simulation tests were carried out in the laboratory. These laboratory tests were extended by investigations carried out by Shell Laboratory Amsterdam. Close co-operation between both the laboratories lead to the conclusion that again the phenomena of silver whiskers resulting from silver sulphide on the silver-plated contact surfaces of components used in the low voltage switchgear assemblies.

As there was no parallel to Durban in the respect of a Sulphur plant next to the switch house it was noticed that the Curacao refinery was cracking a high sulphur containing crude oil from Venezuela resulting in high sulphur content in the ambient atmosphere.
Shortly after this incident, another one incident was received again with a similar short circuit incident in a Singapore refinery and also most probably initiated by silver whiskers. Actually in all three plants (Durban, Caribbean's and Singapore) it was found silver whiskers on relatively new switchgears (early 1970 supplies).

For supplier and the end customer it was a puzzle why this all of a sudden happened (all in a sort of equal time frame). The "big question" became what could be done to avoid the phenomena and above all how to eliminate the spontaneous short circuits.
Therefore, it was essential to undertake a thorough literature study and a number of laboratory tests to determine exactly the origin of the whisker growth and/or to find eventually alternatives for silver plated surfaces offering the same electrical advantages as silver does.
In general, silver plating was needed to avoid an increase of temperature (rise of contact temperature). When selecting another contact material, particular due to a lower conductivity of the contact surfaces contact temperatures increased. Furthermore, emphasize was put on "*what can be done*" to improve the basic design, eliminating the possible growth of whiskers or when unavoidable to eliminate the subsequent risk of short-circuit?
First task was to find out what are the ambient situations needed to grow silver whiskers. Before starting this investigation it was needed to evaluate the questions "*Why do we have silver plated contacts*", "Do we need silver or can we apply alternative materials" in the switchgear designs. From the results of various laboratory tests, the conclusion was drawn up that silver was the very best economical and technical choice.

Beside gold, silver offers superior contact surface resistance characteristics. Tin plating was considered but did not offer the right contact resistance values and more seriously, it is easily subject to sticking when used for sliding contacts. Literature studies showed that tin plating may also be subject to whisker forming and already in 1946 tin whiskers were discovered and described in various publications.
After concluding that silver remained the best alternative in close cooperation with Shell laboratory in Amsterdam, the decision was made to investigate what made silver so vulnerable for whisker forming. Why do the contact temperature in combination with high humidity and the presence of sulphur in the atmosphere give the ideal combination to form silver whiskers?
During laboratory tests subsequently conducted, it showed that by increasing the temperature or the humidity the growth of silver whiskers rapidly increased.
The next photographs show examples of these whiskers, grown under these laboratory circumstances.

II LABORATORY TESTS

With the first test scheme it was assumed that whiskers, as found in the switchgear assemblies, will only develop in a warm, damp and sulphurous atmosphere. These conditions were simulated, by giving the air in a desiccator a degree of humidity of 100% RH (water on the bottom) and placing a jar filled with sodium sulphite and some hydrochloric acid in the desiccator and locating in an ambient temperature of 80°C.

The reaction of sodium sulphite with the hydrochloride acid results in sulphur dioxide ($Na_2 SO_3$+2HCl > 2 NaCl + $H_20 + S0_2$).
The concentration of sulphur dioxide in the surrounding air was approximately 360 p.p.m. As test samples, suspended in this desiccator, silver-plated (5 µm), tin-plated, and nickel-plated contacts of a 125 Amp load switch were used. The tapped thread hole of the terminal was provided with a zinc-plated steel bolt complete as in practice with a flat spring washer. These bolts were tightened with a torque of 15 Nm. This was done since literature indicated that whiskers on tin plated surfaces grow faster if there are mechanical stresses. [1] After the test had lasted during four weeks very small black fibrous growths were visible, but only on the silver-plated contacts. The length of the fibres was of the order of one tenth of a millimetre.

However, due to severe corrosion of the steel bolts the surfaces of the samples were also severely covered with corrosion products from the bolts. This test was stopped therefore.
A new test was started with a lower relative humidity and with a hydrogen sulphite atmosphere instead of sulphur oxide. Three desiccators were taken now and instead of pure water; water with a 21% calcium chloride addition was taken to reduce the relative humidity of the air. The concentration used gives an atmospheric humidity of 80% RH at an ambient temperature of 20 ^oC (Reference VDE 0308) Furthermore, because at Shell's plant hydrogen sulphite was present in the air, the sulphur dioxide (SO_2) was replaced. The desiccators were filled with different H_2S concentrations, i.e. one pot with 100 p.p.m., one with 400 p.p.m. and the third with more than 600 p.p.m. The concentration in the third pot could not be measured by lack of suitable measuring equipment. Similar samples were tested as used in the first test, however, without bolts in the tapped holes and also completed with contacts of the same 125 A load switch as mentioned before. However, now silver-plated (thickness also 5µ) according to the barrel plating method.
Just as with the first test the three desiccators were located in an ambient temperature of 8O^{o}C. After a test period of four weeks black fibrous outgrowths having a length of approx. 0,5 mm could be clearly noticed on the silver-plated contacts coming from the desiccator with the largest H_2S concentration. The parts from the two other pots had blackened, but just less in proportion as the H_2S concentration was lower, and even when using a magnifying glass no whiskers were observed.

III LITERATURE STUDIES and CONSULTATIONS

In the meantime, contact was made with the Technical University in Braunschweig (Germany). At that laboratory whiskers appeared with a length of approx 0,4 mm, which had been grown in three weeks at an ambient temperature of 40 ^oC, an atmospheric moisture of 83 % RH and a hydrogen sulphide concentration of 20 p.p.m. Long whiskers as found on the contacts of a fuse switch were completely new to them.
Meanwhile also contact has been made with the “Naber Laboratory”, being the Dutch telecom laboratory. They also confirmed the fact of whisker formation in a sulphurous atmosphere and they indicated gold plating as a remedy. In addition also were found two articles of A. Keil and Meyer “Haarförmige Kristalle auf metallischen Oberflächen” from E.T.Z. B, Heft 26, 1962 [2] and "Kristallwachstum bei Schwefel einwerkung auf Silber und beim Zerfall von Silbersulfid" from Zeitschrift für Metallkunde, Heft 5, 1960.[3]
Other literature collected dealt only with whisker formation on tin, zinc or cadmium. Such long whiskers as were found at Shell’s were not described.
In the articles by Keil and Meyer however, it was described that the following cyclical process causes the formation of long fibrous crystals on silver surfaces:

- First, at ambient temperature or at least at a temperature of up to 100 ^OC and sufficient atmospheric moisture a layer of silver sulphite is built up under influence of sulphurous gases. This may be accompanied by the formation of short silver sulphite whiskers.
- For the second phase the temperature must rise above 200^{o}C. The silver sulphite will decompose in fibrous silver crystals, which preferably develop on corners and edges. If the cycle is repeated then the whiskers at re-sulphuration will remain and continue to grow during the following reduction process.

If these are the conditions for the growth of long whiskers it was doubtful whether it is real to assume that in switchboards and distribution boards temperatures exceeding 200^{o}C are regularly produced.
In general, high temperatures of 200 ^OC and above do only occur on the knives of fuse links with high-rated currents during fusing at small overloads, but then these high temperatures will not occur in cycles. Also in the article by Keil and Meyer it is thought improbable that temperatures exceeding 200^{o}C develop in switchgear. The assumption was put forward that the presence of ozone, developed by arcs resulting from switching operations, may reduce the reduction temperature. However, the switch concerned at Shell’s was a load break in a feeder panel and was not frequently operated. In an adjacent tray containing a contactor, that was operated regularly no whiskers were found so it was considered a strong influence of ozone very unlikely. If we stick to Keil and. Meyer's theory then it can be concluded that temperatures of 200 ^oC or higher do occur in practical situations
This could be the case if the contact resistances largely increase due to a very thick layer of silver sulphide.

IV EXTENDED LABORATORY TESTS (Elevated temperatures)

For reasons mentioned before, it was measured the voltage drops of the knife contacts of the fuse links, the contacts of the fuse carriers in the fuse-switch and of the knives in the fuse carrier.
During the measurement performed, using a 25 A DC current, it appeared that the voltage drops of these contacts that were severely attacked by sulphur, are much larger than normal (up to twenty times the normal value). Next, the fuse carrier, fitted with a 250 A fuse link, was subjected to a temperature rise test.
After loading the fuse link, with a rated current during 4 hours, the fuse link blew and broke the current without having a reading of the temperature. This was beyond expectation as the IEC requirement is 1.3 x In, fusing time > 3 hours and our fuse links comply with this requirement.

The fuse link was then provided with new fuse elements whereby obviously the fuse link was withdrawn and re-inserted in the fuse carrier. In addition, thermo elements were fitted to both the fuse knives.
A recorder registered the temperature rise.
Measuring leads were connected to one of the knives and the relevant fixed contact to register the voltage drop during the temperature rise test. First the load current was set at 200 A. During the test, which lasted for 50 hours, the temperature rise of the two knives was practically identical and constant and was approximately 45℃. At the very outset the voltage drop of the contact area connected to the recorder was approx 50 mV whereupon it remained practically constant. Then the load current was increased to 225 A.
Immediately the voltage drop over the contact area increased steeply and after about four hours it went straight up to approx 200mV, where upon the voltage drop behaved irregular. The temperature rise of the relevant knife showed a similar pattern and climbed from 60^{o}C to fluctuations around 150 ^{o}C The temperature rise of the other knife was considerably lower and was 70 ^{o}C at the moment the temperature of the knife with the bad contact area fluctuated around 150 ^{o}C. Both the voltage drop and the temperature rise of the relevant knife remained very unstable for about two days. The voltage drop fluctuated between 150 mV and 300 mV and the temperature rise of the knife fluctuated between 130^{o}C and 190 ^{o}C (Fig. 4). Gradually, however the oscillations became somewhat quieter, the voltage drop gradually decreased, interrupted by periods with fluctuations to a value around 125 mV. The temperature rise of the knife of the relevant fuse link developed. Similar and after the fifth day the temperature rise was around 125 ^{o}C. At this moment, the load current was increased to 250 Amp and during the first day the voltage drop remained stationary with a tendency to decreasing. From the above it is clear that in the event of contacts severely attacked by sulphur, the required temperature of 200 ^{o}C and higher, according to Keil and Meyer, must certainly be considered as probable. However, it can now already be concluded, quite irrespective of possible whisker formation, that an atmosphere with such a high concentration of sulphurous vapours as occur at the Shell Curacao refinery is inadmissible. In connection with Keil and Meyer' s theory and the high temperatures as measured, new tests have been started. Bent copper strips have been provided with a 25 u silver layer. As described in the relevant article these strips will be cyclically sulphurized using a damp H_2S atmosphere of 80 ^{o}C followed by reduction at a temperature of approx 300 ^{o}C. This value was chosen as at higher temperatures the reduction process will be accelerated, According to the article 8 hours at 400 ℃ corresponds to 5 days at 200^{o}C.

V CONCLUSIONS and REMEDIES

Talking about - and discussing of - and above all not forgetting doing research on silver whiskers, seems to be an endless task.
Understanding and controlling silver whisker growth is the only remedy.
The silver whisker growth can be controlled according the laboratory tests performed, by eliminating one of the 4 ingredients required for a silver whisker.

1. Silver-plating thickness is of importance [5] It is proven that with increased silver-plating thickness the corrosion film thickness degreases. This silver plated surface subsequently contains lesser copper which element causes stresses in the compound layer, initiating the growth of silver whiskers. [5]

In order to avoid these stresses it is recommended to apply a silver coating thickness ofapproximately 20 mu.

2. Other plating materials such as gold may eliminate the whisker problem, but is usually not applied due to costs and the behaviour of gold under arc conditions. (melting point too low) Tin seems a good alternative to silver, as it is cheap, reliable, easy to plate on copper, but it also develops whisker growth. Moreover, it fails in sliding contact designs as it is subject to severe corrosion under conditions where micro motion occurs. (Please see the “Ten Tin Commands” as defined by Mr. Abbott see [5]. With a 5% added lead the tin plated part can be made lesser whisker sensitive. However in today’s world lead is to be eliminated because it proved to be extremely poisons.
By the application of a reflow process making the tin alloy stress free, stresses can be eliminated and consequently the growth of tin whiskers are avoided.

3. Lubricants containing corrosion inhibitors slow down or may even prevent atmospheric corrosion by sealing the silver plated surface. However, special attention should be paid to its thermal stability and resistance to oxidation and it shall also be inert to corrosive atmospheric components. Another aspect is that some inhibitors do create conductive parts causing eventually failures. Well-known lubricants, like Molybdenum disulphide (MoS_2; Molykote) and PTFE are unfit for this application as they increase the contact resistance resulting in contact failure.

4. Conditioning of the working atmosphere by reducing the relative humidity and the content of sulphur compounds in the switch room. Conditioning the microclimate inside the switchgear assembly.
Sealing off the switchgear itself and keeping it under an overpressure situation, expelling the sulphur compounds outside the switchgear keeps the silver plated parts free from forming silver sulphide. Nowadays a wide variety of low cost carbon filters is available for considering this method.

May be the far better solution is to modify the electrical design of the switchgear assembly in such a way that the results of silver whisker growth are eliminated. Eliminate the possibility of any spontaneous short circuit in the basic design of the switchgear and its components. Furthermore, eliminate the accelerators of the silver whisker growth. One of the strongest accelerators, are high temperatures often due to high contact resistance, (i.e. over 140 ^{o}C according above laboratory tests and noticed from various literature). They should be avoided by maintenance and dedicated design and reliable maintenance free contacts.

VI FUTURE DEVELOPMENTS

Sheffield Hallam University and a Silverware manufacturer in the UK have published in the press that progress has been made on the development of a new sterling silver alloy which is highly resistant to sulphidation (tarnish). Detailed research is needed as the conductive properties of this alloy is not known yet. It is also unlikely that this alloy can be electroplated in the near future without further research. Furthermore as said before new metals, potentially being replacements of silver plated surfaces may result in a better protection of electrical switchgear against "spontaneous short circuits". As sulphur whiskers are described in so many publications and no final solutions are published, it might be the best for the time being to decide to develop electrical switchgear in such a way that in case these whiskers still occur, at least the design of the switchgear avoids any potential short circuit.

VII LITERATURE

[1] A.Jafri. Fighting Whisker Growth in the Communication Industry. November 1972.

[2] Albert Keil and Carl-Ludwig Meyer. Über die Entstehung haarförmiger Kristalle auf metallischen Oberflächen. Elektrotechnisch Zeitschrift. ETZ, Ausg. B, 14. Jahrg. (1962)

[3] Albert Keil and Carl-Ludwig Meyer. Kristallwachstum bei Schwefeleinwirkung auf Silber und bei Zerfall von Silbersulfid. Zeitschrift für Metallkunde 51, (1960)

[4] H. K. Hardy, Fulmer Research Institute, Stoke Poges Buckinghamshire.

[5] B. H. Chudnovsky, D. L. Swindler and J. R. Thomson. Silver whisker growth on power contacts in corrosive industrial atmospheres. Paper No. PCIC-2001-21

[6] Ragnar Holm and Else Holm. Electric Contacts, Theory and Application. Springer-Verlag. Berlin/Heidelberg/New York 1967

[7] J.Whitley. The "Ten Tin Commandments" Connection technology April 1989

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