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Tribologic analyses of a self-mated aluminium contact used for overhead transmission lines

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Abstract. The lifetime of aluminium components is often limited to their poor wear resistance. One example for such aluminium applications are overhead transmission lines. The sore points of these lines are the segments where the aluminium conductors are fixed to the line supports. The fixation is commonly realized via aluminium suspension clamps. Here, a superposition of different loads like traction and bending stresses, clamping forces and different types of wear occurs. To investigate the wear behaviour in these peculiar points, tribologic model tests were carried out. Within the tests, overhead conductor wires and aluminium plates, extracted from suspension clamps were reciprocally slid against aluminium plates (cylinder-on-plate test). The COF and a wear related parameter were recorded constantly. Subsequently, the loaded surfaces were analysed using confocal laser and electron scanning microscopy as well as energy dispersive X-ray spectroscopy. The investigation detected the formation of an oxidized tribologic layer between both components. The tribolayer, which mayor part adhered on the suspension clamps, was mostly formed from material removed from the conductor wires.

Introduction

The main damage of overhead transmission lines occurs at points where the conductors are connected to the line supports [1]. The fixation of the transmission line to the line support is realized with aluminium suspension clamps. The anchoring of the conductor is realized with two rounded half-shells that are bolted together with four screws (fig. 1b) [2]. Although the used devices prevent conductor movements directly under the clamping jaws (keeper/clamp), relative movements are unavoidable in the region between the keeper edge and the edge of the clamp (fig. 1b). The farther the distance to the keeper edge, the larger the movements between the components. These movements are the main reason for the damage of overhead conductors, as they are the cause for wear and fatigue of the conductor wires. The damage mechanism fretting fatigue was identified as the most server damage mechanism.
and the main reason for catastrophic transmission line breakdowns [3]. Fretting fatigue takes place in applications, which are exposed to a specific combination of loads: (a) a relative movement. In the analysed case, these movements are generated by wind induced oscillations of the conductor [4]; (b) a normal force, which is present due to the applied clamping force and (c) a tensile stress, which is generated by the dead weight of the conductor and the applied pre-load [5]. Further performed research found out that the conductor damage in the suspension clamps can be narrowed to an even smaller region (fig. 1a) [6].

![Figure 1a: Wear mark in a suspension clamp](image1a)

![Figure 1b: Mounted suspension clamp](image1b)

In fig. 1a, transverse lines are visible at the bottom of the suspension clamp and on the keeper surface. The visibility of these lines decreases distinctly with an increasing distance to the clamp edge. Whereas the last mm of these lines are coloured in deep grab and are therefore easy to distinguish, the rest of these marks did not undergo a colour change. The grey coloration of these marks is (a) related to a higher degree of oxidation and (b) to a topographic change on the clamp surface. Already published investigations revealed a material transference from the conductor wires to the clamp surface [6]. In contrast, the harder to visualize lines are generated by plastic deformation of the clamp material. The applied clamping force is strong enough that the conductor as well as the suspension clamps/keeper surfaces deforms plastically. The oxidized parts of the wear marks are indicating a gross slide wear regime [6]. In other word, huge relative movements between conductor and suspension clamps occur. The end of these wear marks are defined as the “last point of contact” between conductor and suspension clamp (fig. 1b). The area accentuated with a square (fig. 1a) indicates the region where stick and slip occurs (also called mixed mode). Such movements are known to be the most server mode for fretting fatigue crack initiation [5, 7]. On the right side of the square, no relative movements occur [7, 8].

As shown in fig. 1b, conductors for overhead transmission lines are built-up by many aluminium wires, which are organized in layers. Independent from the conductor type (e.g. pure aluminium conductors, steel reinforces conductors or aluminium alloy conductors), the outer layer of the conductors are made of aluminium, e.g. aluminium alloys. Even though wire breaks occur in the external and the internal layers, evidences for preferred first wire breaks in the external layer were found [8]. The reason for a preferred crack initiation in the outer layer is seen in the contact with the suspension clamp. So far, no detailed tribological analysis of the conductor wire/clamp contact was carried out. As shown in fig. 1 and described elsewhere [6], a material transfer from the conductor wire to the suspension clamp occurs. This means, that the mayor damage occurs in the conductor and not in the clamp. An opposite behaviour would be more desirable, as suspension clamps could be renewed easier that the large conductors. Considering that tests with real conductors are very costly, the aim of the present investigation is to verify, if tribological model tests with dry sliding conditions can reproduce the damage type observed in the conductor/clamp contact. It needs to be mentioned that the used model
test was chosen to reproduce the tribological aspect of the contact. The fretting fatigue behaviour of the conductor wires cannot be investigated with the chosen test method, as no tensile stresses have been applied on the tested wire.

It is known that a reduced coefficient of friction (COF) has strong effects on the wear behaviour and the generation of fretting fatigue cracks [8, 9]. Therefore, it is expected that the lifetime of overhead transmission lines can be extended by modifying the surface of suspension clamps. As described above, this work focuses on the evaluation of the tribologic contact between conductor and clamp. The impact of the COF on the wear and fretting fatigue behaviour will be part of future research.

Materials and Methods:

The dry friction tests were carried out using specimens taken from an IBIS overhead conductor, which consists of an AA 1350-H19. The prefix H19 indicates that the wires were die drawn at room temperature. The nominal chemical composition of the wires are shown in table 1. The wires of overhead conductors are helically bundled to allow isotropic movements (radial direction). Due to the winding of the wires, the extracted specimens had small flections, which could not be completely removed by straightening. Such deflections negatively influence the tests results, as they avoid a plane line contact between cylinder (wire) and plate (suspension clamp). To diminish such influence, the size of the cylinder wires was limited to a length of approximately 7.8 mm. The preparation of the specimens was executed using a mounting device with a drilled retainer for the specimen (average specimen diameter 3.15 mm, diameter of the retainer 3.2 mm). To trim the cylinders on their testing length, the wires were fixed in the mounting device and both ends were grinded (abrasive paper Mesh 800) until the final length was reached. To avoid edge effects during the tests, the edges of the cylinders were manually rounded using the same grinding paper.

Most of the nowadays-used suspension clamps are made of aluminium alloy SAE 305 by mould casting. As the manufacturing process strongly influences the microstructure and the surface conditions of the devices, the used specimens were extracted from unused suspension clamps. The fabricated specimens for the cylinder-on-disc tests had a diameter of 24 mm and a height of 7.5 mm. The nominal chemical composition of the AA SAE 305 is listed in Table 1.

| Table 1. Elements contained in the tested materials in %. |
|------------------------------------------------------------|
| Materials                                                  | Al | Fe | Si | Mn | Zn | Cr | Cu | Mg |
| Conductor IBIS (AA 1350-H19)                               | 99.5 | 0.4 | 0.1 | 0.05 | 0.05 | 0.01 | 0.05 | - |
| Suspension clamps (SAE 305)                                | 86.0 | 0.5 | 12  | 0.35 | 0.35  | -  | 0.25 | 0.1 |

As shown in table 1, the material of the conductor can be considered as low alloyed aluminium, whereas the suspension clamp contains higher quantities of alloying elements (mainly silicon). Since the surface roughness influence the COF and the wear behaviour [10], all tests specimens were grinded and polished until they reached an equal surface condition (Ra = 1.16 µm).

The friction and wear tests were executed with a reciprocating wear tester (Optimol). A section of the testing equipment is shown in fig. 2.
The mounting of the tests were carried out in the following sequence. First, the prepared wires were clamped in the specimen holder (top side), which was fixed in the testing machine subsequently. Afterwards, the clamp material was positioned under the wire. To control if a plane contact occurred, both counterparts were slowly driven together. In case of a visible gap between the specimens, the clamp material was readjusted until no gap was noticeable. The test rig operates with unilateral movement. More precisely, the clamp material is fixed on the base (bottom) of the wear tester, while the specimen (top) is moved reciprocally to the left and the right.

The tests were carried out using a normal force of 20 N, a frequency of 200 Hz and a lateral displacement of 100 µm for 90 min. Three specimens were tested under these conditions. As the results showed a good accordance, no further tests were performed.

The COF and the vertical displacement (combined wear depth of the interfaces) was measured continuously by the testing machine. To abolish disaccords, the term vertical displacement will be explained more detailed. Before the start of the tests, the vertical displacement was set to 0. After this reset, any occurring wear resulting in a vertical displacement of the specimen holder (top side) can be recorded by the test machine. The result of this method is not the total wear volume (Due to the fact that wear occurs on both surfaces and in different lateral extensions), but it allows the detection of wear and friction effects resulting in vertical displacements. Such data is especially valuable for the investigation of the running-in phase, which cannot be analysed with post-test measurements (in the case of long lasting test cycles).

The measurement of the total wear volume (clamp and wire specimens) was realized with a confocal laser microscope (Olympus/Lext). The wear volume survey of the clamp specimens did not require further data processing. The determination of the wire wear volume required the use of a subsequently performed data processing. Fig. 3 shows the schematic drawing of the wire cross section after the wear tests. With the use of the confocal laser microscope, the dimension of the generated wear marks can be easily measured (via polygon adaptation). For the wear volume calculation, the wire wear mark was considered as rectangular (Dividing the measured wear mark area though the specimens length). Using this technique, a mean wear mark width can be calculated. In fig. 3, this theoretical wear mark surface is labelled with the letter s. With the additional assumption that the wire is perfectly circular, the wear volume can be calculated using equation 1 and 2.
Figure 3: Schematic view of the wire cross section

- $V_{\text{wear}} = \left( r^2 \cdot \arccos \left( 1 - \frac{h}{r} \right) - (r - h) \cdot \sqrt{2rh - h^2} \right) \cdot l$
- $h = r - \left( \sin \left( \arccos \left( \frac{s}{r} \right) \right) \cdot r \right)$

In the shown equations, $r$ represents the diameter of the wire, $s$ the normalized wear mark width, $h$ the depth of the wear mark. To facilitate the understanding of fig. 3, the removed wear volume is shown in green.

The microstructure analysis as well as the investigation of the chemical composition were performed using a Scanning Electron Microscope (SEM) equipped with a Jeol 7500 Energy dispersive x-ray spectrometer (EDX). Beside the EDX measurements on the wear mark and the different bulk materials, a cross section scan of the wear mark (clamp) was performed. Therefore, the clamp specimens were cut in a 90° angle to the wear mark. Subsequently, the cut specimens was embedded and polished to scan the depth profile of the wear mark.

Results:

The used friction and wear tester measured the COF and the vertical displacement constantly during the tests. In fig. 4, the measured COF values are shown.
The results shown in fig. 4 illustrate a clear running-in behaviour. In the first minute, the COF increased abruptly to a value of two. After this overshoot, the COF decreases to a value of approx. 1.15. This running in phase took approx. one minute. In the following eight minutes, the COF increased slightly to 1.3, where it reached its steady state value. The deviation between the results are negligible. The vertical displacement, also recorded by the wear tester, is shown in fig. 5.

The measurement of the vertical displacement revealed strong deviation between the tested specimens. After the running-in phase, the slope of all tests stabilized. The main difference between the tests
occurred during the running-in phase. Here, the measure vertical displacement of the three specimens jumped to 10 μm, 28 μm and 18 μm, respectively.

After the wear tests, the wear volume was determined using a confocal laser microscope. The investigation of the generated wear marks revealed a strongly irregular topography. The wear marks on the clamps showed regions where material was removed from the surface, as well as areas, which were higher than the original surface level. In the built-up regions, material was deposited on the clamps. One representative colour image as well as a height profile of the same wear mark is shown in fig. 6.

The colour image of fig. 6 reveals that most of the wear mark is higher than the original surface. The homogeneous violet colour distribution around the wear mark designate the unloaded surface. The darker colours indicate areas where material has been removed from the clamp surface. The brighter colours indicate areas that are high than the original surface. Here, material was transferred from the wire to the clamp. The additionally shown height profile visualizes the explained results with a topographic graph. To facilitate the understanding of the height profile, the unloaded surface level was set to 0. Due to this Y-axis adjustment, the negative values represent areas where material was removed, whereas the positive values denote a material deposition.

The software of the confocal laser microscope allows the determination of the wear volume. Therefore, an imaginary plane is visually adjusted congruently to the unloaded surface. Using this reference plane, the software is able to differentiate the deposited from the removed wear volume. According to this method, three different columns are presented in table 2. The wear volume is normally represent as a positive value. In the present study, a small amount of aluminium has been removed from the suspension clamps. On the other hand, a comparably high amount of material has been transferred to the clamps. Therefore, the total wear volume is presented with a negative sign. The column “total wear volume clamps” shows calculated values, where the removed wear volume has been subtracted from the deposited wear volume. The column “removed volume clamps” lists the amount of removed clamps material and the column “wire wear volume” represents the calculated wire wear volume (calculation method explained in the method section).

Table 2. Determined wear volume clamps and wires.
Similar to the vertical displacement measurements, the listed total wear volume of the clamps show some differences between the tests. Comparing the measured wear volume of the clamps with the calculated wear volume of the wires, a good accordance was found. The maximum deviation between the values is 10%. Considering that not all removed wire material was transferred to the clamps (loose abrasive particles were found on and around the wear mark), a good accordance can be assumed. The material removed from the clamps was found to be small for all tests.

The microstructural analysis of the wear marks was carried out using SEM and EDX techniques. Three representative images of one clamp/wire pair is shown in fig. 7. Fig. 7a images an overview of the wear mark on the clamp. Fig. 7b shows the wear mark on the wire and fig. 7c represents a higher resolution image of the wear mark on the wire.

As already shown in fig. 6, a massive material transfer from the wire to the clamp took place during the tests. This phenomenon is also visible in fig. 7a, where mounds and cavities above the ground level can be recognized. In this overview picture, the wear mark can be clearly differentiated from the plane, unloaded surface. The wire wear marks show a similar topographic structure with mounds and cavities (fig. 7b). Furthermore, scale-like structures are visible on the surface of the wire wear mark. Such structures were also found on the clamp wear marks, nonetheless have not been illustrated in fig. 7a. Fig. 7c pictures a higher resolution image of the wire wear mark. Here, a tribologically unloaded surface is visible between two massive tribolayer scales (designated with a white arrow).

To gain more clarity for the interpretation of the SEM images, EDX measurements were carried out. The results are listed in table 3.

| Number of test | Total wear volume clamps (10^6 µm³) | Removed volume clamps (10^6 µm³) | Wire wear volume |
|---------------|------------------------------------|----------------------------------|-----------------|
| 1             | -64.35                             | 0.63                             | 64.29           |
| 2             | -72.84                             | 0.37                             | 67.12           |
| 3             | -71.22                             | 0.15                             | 78.88           |

Table 3. Results of the EDX measurements

| Position                  | Al  | C  | Si  | O   |
|---------------------------|-----|----|-----|-----|
| Unloaded clamp            | 85.7| 4.7| 7.9 | 6.7 |
| Unloaded wire             | 89.7| 7.2| -   | 3.2 |
| Wear mark clamp           | 28.8| 5.7| 0.3 | 65.1|
| Wear mark wire            | 33.8| 3.6| 2.5 | 60.1|
| Cross section wear mark   | 25.1| 9.3| -   | 65.6|
The executed EDX measurements confirm the data taken from the specification sheet of the manufacturers (table 1). The main difference between the aluminium wire and the aluminium clamps is the high amount of Si in the clamp material. The concentration of the other alloying elements shown in table 1 is too small to be detected with the used method. The main difference between the wear marks and the unloaded bulk material is the increased amount of oxygen. In this research, the increased oxidation state was used to differentiate the tribologic layer form the unloaded bulk material. The measurements carried out on the cross section of the clamp wear marks did not show a gradient in oxygen concentration or any other element, for which reason only one representative result is shown in table 3.

Discussion:

The analysis of the COF results revealed a pronounced running-in behaviour. In the first minute of the tests, the COF increased to a value of two. Such overshoots are typical for sliding wear tests with aluminium/aluminium friction partners and are contributed to the deformation of asperities [further named µd] [11, 12]. In the beginning of the tests, the contact between the two surfaces mainly occurs via few surface asperities. This means that the actual area of contact is drastically reduced. Due to the applied normal load, vertical evading is not possible, whereas wedged asperities need to deform in order to allow lateral movement. Especially the high COF values during the running-in phase are generated by the deformation of asperities [13]. In this initial phase, the biggest asperities are smoothened. Nevertheless, µd is also present after the running-in phase, as asperities are constantly built and unbuilt. The initially high friction values stand in good accordance with the found high vertical displacement (fig. 5). These results reveal that a relevant part of the wear occurs in the first seconds of the tests. The following decreased COF values are related to the smoothening of the asperities and the formation of a tribologic layer.

In the further course of the tests, the COF first decreases to approx. 1.15 and afterwards increases to its steady state value of approx. 1.3. In this transition time, surface adhesion [further named µa] plays an important role, what was not the case during the running-in phase. Due to the fact that surfaces are normally contaminated or, in the present case, oxidized, the importance of µa is little during the running-in phase [14]. µa contributes strong to COF, when the friction partners are self-mated. Removed aluminium clusters easily attach via interatomic bonds to the opposite surface when consisting of the same material [14]. After asperity deformation occurred and at least partially unoxidized clusters were detached from one surface, the integration on the friction partner or the tribolayer is easily possible.

Another friction and wear phenomena that contributes to the high COF is micro ploughing of hard asperities or abrasive particles [further named µp]. Similar to µa, µp gains more important after the running-in phase, as abrasive particles first need to be generated (present study). It is expected that abrasive wear particles are formed directly after the running-in phase. The generation of abrasive wear particles in self-mated contacts normally occurs in the following sequence: (a) asperity deformation (b) extraction of the softer sliding partner (c) oxidation of the removed or transferred material. Other research showed that material transfer occurs already after a low number of cycles [15]. In the present case, the softer wire material was transferred to the harder clamp surface. After the test specimens have been removed from the testing machine, dark abrasive particles were found on and around wear mark. Their presence proved the generation of loose abrasive particles. To sum up, the presence of all three described friction and wear phenomena could be demonstrated with the performed tests.

The results of vertical displacement curves stand in well accordance with the discussed results of the COF. The high COF values during the running-in phase are fitting well to the initially strong vertical displacement alias strong material loss between the wear partners. In literature, such severe forms of wear characterized by a macroscopic material transfer between solid surfaces is called galling [16]. Galling arises when strong plastic deformation occurs on at least one of the contact partners [17]. The
tested materials have a comparably low yield strength. Therefore, plastic deformations occur even at low contact forces. Due to the reduced real contact area (asperity contact theory), even small normal loads are sufficient to generate plastic deformation. Other researchers, whose used the same experimental setup (cylinder-on-plate), found out that galling on aluminium (6061-T6) already occurred at nominal stresses 0.07 times the yield strength of the material [15]. The mentioned outcome reinforces the conclusion that the high COF and vertical displacement values in the beginning of the tests are mainly attributed to \( \mu_d \).

After the running-in process, the vertical displacement increased steadily until the end of the test. It is assumed that the asperity deformations in the beginning of the tests lead to a fast formation of a tribolayer. After its formation, the generated vertical displacement was found to be stable. Here, the relative movement occurs either between one of the friction partners and the tribolayer (which is attached to the opposite surface) or in between two tribolayers which are attached to their respective surfaces. As a strongly oxidized tribolayer was found on both friction partners, the latest possibly arose during the tests. Certainly, the tribolayers are further exposed to wear and asperity deformation/formation continues, whereas the vertical displacement shows a more or less stable slope. The comparison of the post-test determined wear volumes (clamp/wire) are standing in well accordance with each other as well as with the vertical displacement values. The differences between the single measurements first seem to be extraordinary. However, the microscopic views of the loaded surfaces can explain the found differences. As shown in fig. 8, the form and size of the wear marks differs strongly from each other.

![Figure 8a: Wear mark on the conductor (test 3)](image)

![Figure 8b: Wear mark on the conductor (test 1)](image)

The found differences are attributed to the not perfect line contact between the wire and clamp specimens. Even though their plane contact was visually verified, a complete contact over the entire wire length was not be reached for all tests. Comparing the image shown in fig. 8b, the right part of the wire did not have contact to the clamp surface in the beginning of the tests. After some cycles, the wear of the wire increased and the so far unloaded part of the wire was put in contact with the clamp surface. These stated differences are seen to be responsible for the deviations in vertical displacement results of the running-in phase (fig. 5).

The images taken with the SEM clearly show the formation a tribolayer (fig. 7). Different from the unloaded surface, the tribolayer has a scale-like structure, which also inhibits a higher brightness in the SEM images. Brighter reflexes indicate a stronger oxidation (present study). The scale-like textures are generated by the relative movement and the thereby generated grading of the asperities. Fig. 7c represents an amplified image of the wire wear mark edge. Here two surfaces are visible. (a), the bumpy oxidized surface of the tribolayer and (b), the smooth homogeneously flawed surface of the wire. The shown surface structure is typical for wire-drowned materials. Important to notice is that regions of unloaded wire surface are visible inside the wear mark (arrow). This shows that the lateral extension of the tribolayer cambers over the unloaded surface. The cylindrical shape of the wire facilitates this movement. It is assumed that with proceeding test cycles, parts of this overlapped material were detached from the wire and formed the found loose wear debris beside the wear mark.
The EDX analysis was used to clarify the differences between the clamp and the wire specimens as well as the formed tribolayer. As shown in table 3, the main differences between the wire and the clamp material is the amount of silicon. The carbon and the oxide detected in both materials can be related to the natural protection layer of the aluminium and negligible contaminations on the surface of the specimens. The similar results on both wear marks confirmed the visual impression that both surfaces are covered with a tribologic film. The differences in oxygen and carbon deviate slightly. Interesting to notice is that the measurement executed on the wire showed a slightly increased amount of silicon compared to the measurement on the tribolayer of clamp. As shown in fig. 6, there are some areas where the surface of the clamp material has been removed. Even though the main wear volume origins from the wire, small amounts were also removed from the clamp, for which reason silicon was also detected in the tribolayer of the wires. The cross-section of the wear mark was scanned via EDX to examine if gradual changes in the element compositions are present. Such changes could not be found, whereas only one result is shown in table 4. A comparison of the element concentration found in the cross-section with the results of the tribolayer did not reveal relevant differences.

After the straight tribologic discussion of the results, the evaluation of the relevance for the transmission line applications is done. As already described in the introduction, the performed model tests did not aim to reproduce fretting fatigue conditions (due to the missing tensile stress in the wire). However, the wear and tribologic conditions of the real application seem to be well represented by the performed tests. Similar to the in fig. 1a shown wear marks, a material transfer from the wire to the clamp was observed with the used test conditions and parameters. The lateral displacement of 100 µm stands in well accordance with the expected movement of the conductor close to the last point of contact. For investigations of the fretting fatigue behaviour of the wire, the stroke should be reduced, as the crack initiation occurs closer to the clamp centre.

Based on the detailed evaluation of the wear and friction behaviour of the aluminium/aluminium contact, the superiorly aim of tailoring contact conditions between conductor and suspension clamp can be realized with the same test procedure. Tests with surfaced that provide reduced COF and lower wear rates will be tested to delay wire damage and therefore improve the lifespan of overhead transmission lines.

**Conclusion:**

The wear and friction behaviour of aluminium wires used for overhead transmission lines was investigated using a cylinder-on-disc wear tester. The major findings of the carried-out experiments are the following:

- The aluminium/aluminium contact led to a sever wire damage after the applied friction/wear test.
- Adhesion between the materials, deformation of asperities and ploughing of generated abrasive particles were identified as reasons for the high COF and the high wear damage.
- After an initial smoothening process of the surfaces, a tribolayer was formed on both surfaces.
- The tribolayer mainly consist of oxidized aluminium.
- After an initially high COF values, the COF stabilized at a level of 1.3.
- The used test method was found to be adequate for the tribologic evaluation of the contact condition present in the described application.

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