Formation of micro-cracks at the surface of a high voltage cable screen induced by aluminum corrosion

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ABSTRACT

The main purpose of this study is to investigate the adhesion between corroded aluminium conductor strands and the semi-conductive cable screen. In this paper it is proposed that increased adhesion is one of the pre-requisites for the local degradation of the semi-conductive cable screen causing severe water treeing in the XLPE insulation. A model test set-up was developed and used including samples with a dried corrosion layer between a heat pressed semi-conductive cable screen and an aluminium metallic surface. The results show that the adhesion was strongly increased when the Al surface was corroded.

KEYWORDS

HV subsea cables, water treeing, stress induced electrochemical degradation, corrosion, adhesion.

INTRODUCTION

There is an increasing demand to produce lighter power cables for deep water applications and a major weight element in a cable is the conductor. Today the inter array cables are normally equipped with copper conductors. By replacing the copper with aluminum, the weight at the same electrical cross section is halved. For dynamic cables, a wet design is preferable since a metallic water barrier adds weight and complexity. However, there is a risk of increased water tree growth due to degradation of the inner semi-conductor if liquid water is present at the conductor strand surfaces [1].

SEM investigations have revealed that the interface between the semi-conductive screen and metallic strands (cable conductor) contains small micro-cracks. These structures were found to generally occur at points of corrosion at the surface of the aluminum conductor (strands) [1]. It has previously been proposed that this was a result of an electrochemical reaction between the aluminum conductor and the carbon black of the inner semiconductor in combination with mechanical stress and called "Stress-induced electrochemical degradation" (SIED) [2].

The hypothesis presented in this paper is that the corrosion layer at the aluminum conductor strand surface strongly increases the adhesion between the conductor and the conductor screen. When this corrosion layer cracks [3], the adhered semi-conductive surface will be subjected to axial forces at the surface of the semi-conductive conductor screen material inducing micro-cracks. It is likely that the residual mechanical stresses in the insulation system after extrusion contributes to the inception of the micro cracks [4].

The main purpose of this paper is to examine if corrosion can cause an increased adhesion between the aluminum surface and the semi-conductive cable screen using simple model samples.

EXPERIMENTAL

To test this hypothesis, we have developed a simple model system (Figure 1, left) to test the adhesion between semi-conductive materials and aluminum, and investigate the effects of corrosion.

To measure the adhesion energy between a coating layer (made of the semi-conductive material) and a metal surface (aluminum), we used a blister method where the setup is based on the formation of a blister by injecting nitrogen gas under pressure between the coating and the substrate. The adhesion energy is determined by recording the pressure as a function of the recorded blister radius development.

Blister Experiment

The adhesion between the semi-conductive material and the uncorroded or corroded aluminum surfaces were investigated by using the blister method. A blister is formed by injecting nitrogen gas under pressure between the coating, i.e., the semi-conductive material, and the substrate, i.e., the aluminum disc. A laser is moved over the blister with a speed of x cm/s. Two programmable step engines were used to measure the blister profile and thereby the radius of the blister between successive pressure increases (0.5 bar steps). The adhesion energy is determined by recording the pressure as a function of the recorded blister radius development and calculated using Equation 1.

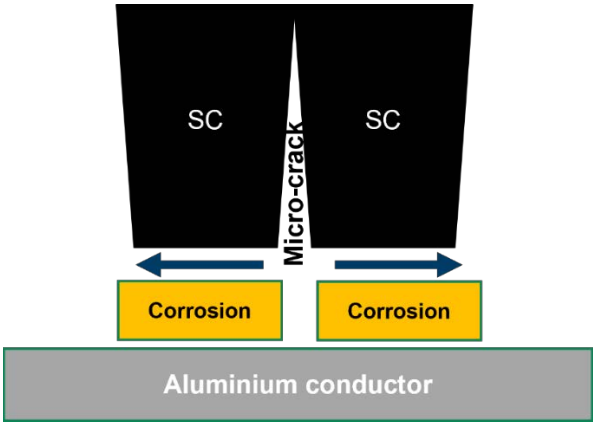

Figure 1: Schematic of a model system to test the adhesion between semi-conductive materials and aluminum and investigate the effect of corrosion (left). Aluminium disc to be coated with the commercially graded carbon black semi-conductive screen (right).

The pressure observed when the edge of the blister starts to propagate was used when calculating the adhesion energy. This is an estimate of the critical pressure and the radius "a" of the blister before the edge moves. The thickness of the semi-conductive layer is measured outside the deformed area at three places after it has been blown off for the whole disc.

We follow the blister development with increasing pressure and can calculate the adhesion energy [5]:

$$G_a^3 = \frac{a^4 p^4}{17.4\, E\, h} \qquad (1)$$

Where p is the pressure needed for the blister to increase the diameter (temporary loss of adhesion without collapsing the blister), a is the radius of the blister before the diameter increase, h is the thickness of the semi-conductor material and E is the E-modulus of the material. It is therefore possible to calculate the adhesion energy several times on the same object if the blister develops without cracking.

The schematic of the blister setup is shown in Figure 2. Outside the hole (1.2 mm) there is a slip zone (2.5 mm) where Teflon spay is applied. This low-adhesion region around the hole is where the initial blister will form. This is done before heat pressing of the semi-conductive screen material. After heat pressing, a semi-conductive coating is sprayed to a very thin layer thickness (~20 µm) to significantly enhance its reflection properties, which is required for the optical (laser) measuring system.

The aluminum discs with the semi-conductive screen material were mounted in the blister rig which clamped the coated disc downward to stabilize it when the gas pressure was applied. Ambient pressure was initially applied, and the laser was moved along the sample and directly over the peak of the blister. Two additional parallel scans were performed at a distance of 1 mm from the first scan. This gave a baseline for the blister. The full scan was taking approximately 5 minutes.

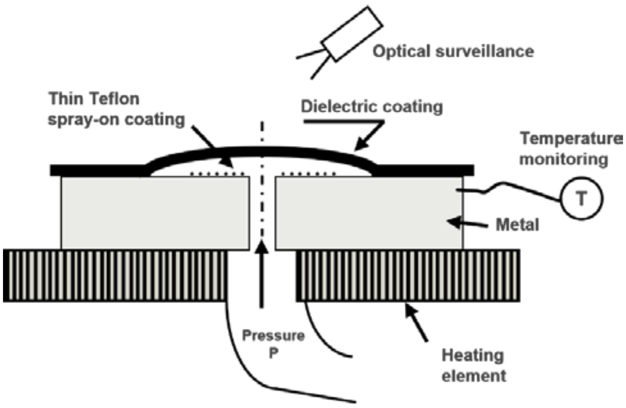

Figure 2: Schematic of the experimental setup for blister test, adapted from [6]

The pressure was then increased by pressure steps of 0.5 bar intervals, and the blister was immediately scanned, followed then by a waiting time of another 5 minutes before the blister was scanned again for 5 minutes without increasing the pressure. This was repeated until the semi-conductor was eventually significantly detached from the aluminum disc.

In terms of spatial blister measurements, they were conducted by using a laser distance sensor by LMI, model LDS 90/45. It was programmed to sample at 101 equally spaced points along the axes of measurement. At each point, 10 height measurements were taken, and their average was logged to reduce any inaccuracies due to reflections for a specific measurement. Measurements were programmed to be conducted only in one direction (left to right). The laser was moved in X and Y direction with the help of two step motors, controlled through a computer by XILab Interface software, that was preprogrammed to automate all measurements. During the blister profile measurements, the laser was moved along one axis in a forward movement for a total distance of 10 mm, mid-point being the initial location of the peak of the blister.

The reproducibility is controlled by performing measurements on twelve different discs, six non-corroded and six corroded ones.

Aluminum discs preparation

The blister experiments were performed using aluminum (Al) discs with a commercially available semi-conductive cable screen material. Prior to heat pressing of the screen material to the Al surface, the Al discs were wet sanded with 2000 grit sandpaper and then polished using a 6 µm diamond powder and finally a 3 µm diamond powder. After polishing, all samples were cleaned with 2-propanol using lint-free cloths. To corrode the aluminum discs, they were immersed in local tap water for 72 hours at 50 °C. Before heat pressing the discs with the screen material, Teflon spray was applied around the blister hole at the disc center (Figure 1, right).The blister hole was then sealed with a metal plug to allow for an even layer of semi-conductor and preventing the semi-conductor material from filling the blister hole during the molding process.

The semi-conductor was molded onto the aluminum discs using a platen press. Before molding, the semi-conductive material was machined into 2 mm sheets in a roller mill. Approximately 2 g of the rolled material was put on the discs, which were then inserted into the press. The molding procedure consisted of three stages: first, the discs with the semi-conductor on top were pre-pressed at 120 °C under low pressure (3 bar) for 10 minutes; then they were heated to 175 °C at high pressure (25 bar) for 30 minutes to cross-link; last, they were cooled (water cooling) for 10 minutes. This procedure gave a semi-conductor layer thickness of 0.5 mm (about 1.7 g). By using shims, the semi-conductor thickness was reduced to ca 0.30 mm. Once the coated aluminum discs were ready, a rounded metal pin was inserted into the blister hole to carefully lift the semi-conductor close to the center hole, creating an initial blister and avoiding the risk of having semi-conductor adhering inside the blister hole.

Profilometry

Surface roughness parameters were measured optically using a 3D Profiler (BRUKER Contour GT−K) in the vertical scanning interferometry mode. Each scan had a diameter of 40 mm, with a 20% overlap between the scans [7], [8]. The surface roughness parameters used in this work were calculated using the Vision64 software from BRUKER by employing the S-parameters (height) analysis toolbox. They are listed below and illustrated in Figure 3:

- arithmetic mean height/roughness (S_a),
- RMS height/roughness (S_q),
- the maximum profile peak height (S_p)
- the minimum profile peak height (S_v).

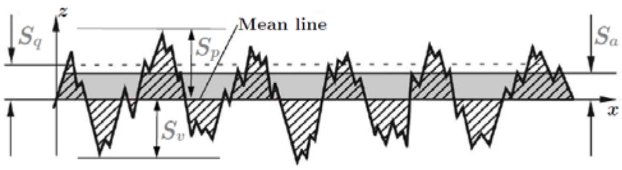

Figure 3: Reference sketch illustrating the S−height parameters in a 2D surface profile [9].

The parameters, S_a and S_q, represent an overall measure of the surface texture, while S_p and S_v show the maximum variation between the peaks and dips/valleys. Since S_a and S_q are derivatives of each other, they follow/indicate the same trend

RESULTS AND DISCUSSION

Profilometry

To determine the influence of the surface roughness of aluminum on the adhesion energy of the semi-conductive screen material, non-corroded and corroded surfaces were investigated. The 3D surface topography of each surface is shown in Figure 4. Surface profiles of the same sections of the non-corroded and corroded surfaces clearly demonstrate sthe change in the roughness and irregularity after corrosion. The corroded surface appears to be quite rough with an irregular pattern of spikes, whereas the non-corroded surface exhibits a much smoother and regular profile.

To quantitatively assess the surface roughness, S-height parameters were calculated from the measurements (see Table 1). The smooth, polished (non-corroded) surface has a mean surface height S_a value of 0.26 µm while that of the corroded aluminum disc is about 2.7 times as high with a value of 0.706 µm. Similarly, S_q is higher by a factor of 2.3 in the case of corroded surface. Corrosion seemingly resulted in higher peaks (S_p) and deeper dips/valleys (S_v) at the surface by factors of 3.4 and 4.7, respectively.

Table 1: Measured characteristic values of surface roughness S-parameters of the examined corroded an non corroded aluminum samples.

Samples	Roughness S-parameters (µm)			
	S_a	S_q	S_p	S_v
Non-corroded	0.260	0.528	14.826	-7.893
Corroded	0.706	1.224	69.941	-27.175

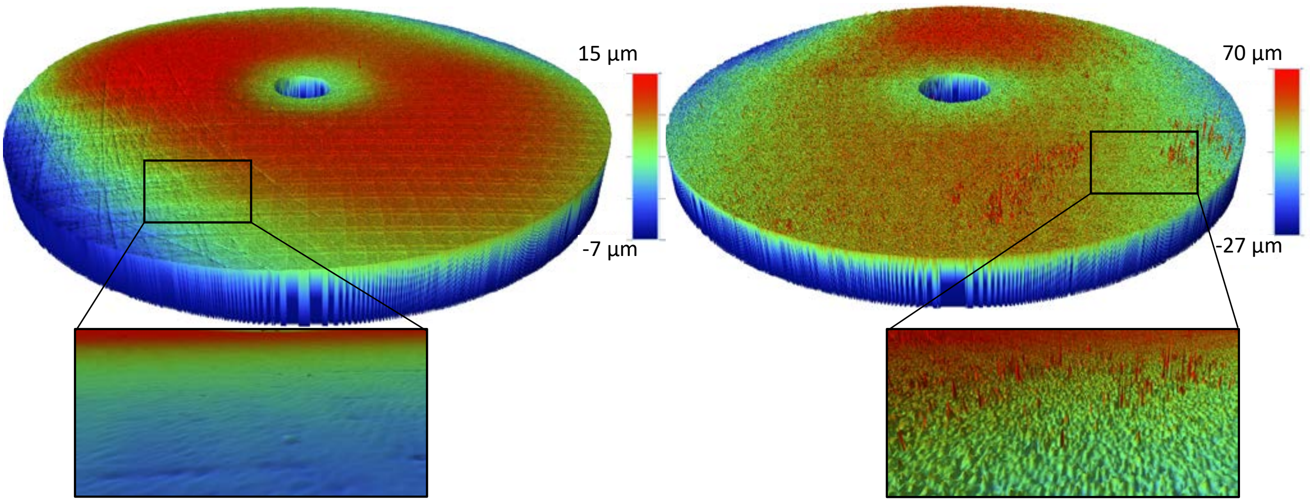

Figure 4: Surface roughness profiles of non-corroded (left) and corroded (right) aluminum plates measured by profilomertry.

Blister test and adhesion energy estimations

The results of the adhesion energy measurements after performing the blister tests are presented in Figures 5 and 6. The blister shows a dynamic movement (mostly in height) after each pressure rise. For the first pressure rise a drop in the pressure is observed between the forward and return movement due to the initial formation and stretching of the material forming the blister. For higher pressures the pressure remains stable (between each forward movement) consistent with a very small blister volume increase.

Figure 5 shows an example of a measurement of the height of the blister versus its radius obtained on a corroded aluminum disc covered with the semi-conductive material. One can observe that the blister increases, continuously lifting the semi-conductive material at the center of the disc until a limit is reached (in the illustrated case, 9.9 bar) where the semi-conductive material is starting to lose its contact with the Al disc. This was observed for all samples, but one case followed by the almost instant rupture of the semi-conductive layer.

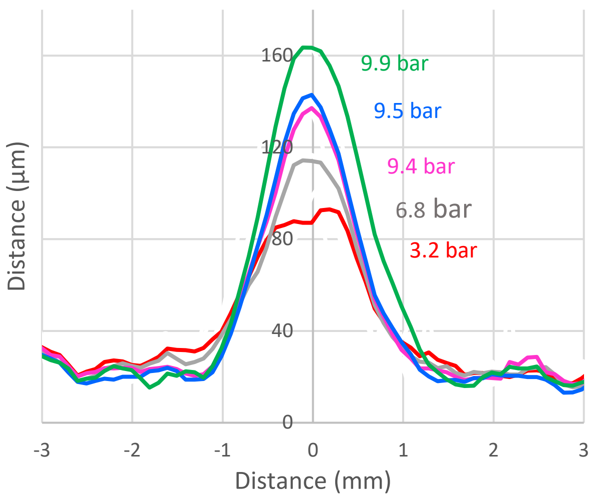

Figure 5: Blister development along the X-axis scan (smoothed data plot) for different pressures between aluminum and semi-conductor with a corrosion layer in between.

Correlation between adhesion energy as a function of surface roughness is illustrated in Figure 6 and summarized in Table 2.

The results show that corroded surfaces have a higher value of adhesion energy compared to non-corroded and smooth surfaces. The adhesion energy necessary to remove the semi-conductive coating from the aluminum disc is on average three times higher, as illustrated in Figure 6. The adhesion was probably improved by the higher surface roughness or equivalently the increase in the effective contact area for the corroded sample when compared to the smooth and polished surface.

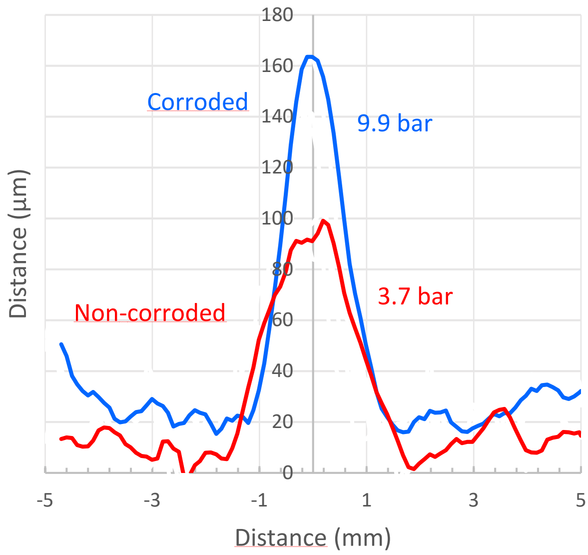

Figure 6: Difference necessary to reach a slip of the buble between a non-corroded and a corroded sample.

Table 2: Adhesion energy measured for the different non-corroded and corroded samples.

Samples	Adhesion Energy (J/m^2)	
	Non-corroded	Corroded
1	28,48	43,66
2	38,13	144,17
3	12,86	91,12
4	16,80	85,84
5	26,25	59,62
6	41,65	72,94

CONCLUSION

It has previously been reported that surface corrosion of conductor strand members can cause severe degradation of the semi-conductive screen in intimate contact with the corrosion in cables with aluminium conductors. This work addresses this phenomenon and in particular the adhesion energy of the screen- aluminium surface.

From this work it can be concluded that

- Corrosion of an aluminium surface causes a significant increase of adhesion energy compared to reference (non-corroded) surface.
- The increase of adhesion is likely due to the increase of surface roughness due to corrosion of the aluminium surface.
- The blister test can be used to study the impact of corrosion on the adhesion energy of polymeric layers.

For a real service situation, the corrosion will take place when the conductor screen is in intimate (but not adhering well) contact with the aluminium strand. The corroded local area will then be wet during corrosion, with corrosion products deposited at the screen surface. This is different from what is studied here and will later be closer examined.

ACKNOWLEDGMENTS

This publication has been produced with support from the LowEmission Research Centre (www.lowemission.no), performed under the Norwegian research program PETROSENTER. The authors acknowledge the industry partners in LowEmission for their contributions and the Research Council of Norway (296207).

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GLOSSARY

HV: High Voltage
XLPE: Cross-linked polyethylene
SIED: Stress-induced electrochemical degradation
SEM: Scanning Electron Microscope