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***Technical paper***

# Corrosion Study of Galvanized Ultra High Strength Steel Reinforced Overhead Transmission Conductors

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## Abstract

Overhead high voltage transmission conductors used worldwide are produced in several configurations. A multi-strand conductor of the type ACSR330 is typically used for 275 kV overhead transmission lines. The conductor is composed of 7 inner strands of Ultra High Strength Galvanized Steel for the mechanical support of the conductor and 26 strands of high conductivity Aluminum wires meant for power transfer over long distances. During the use, weather conditions and power fluctuations tend to degrade the properties of these conductors. In the present work, study of the state of galvanization and oxidation of an ACSR330 conductor is undertaken with a view to understand the effectiveness of the loss in corrosion protection and changes in the zinc coating on the galvanized steel strands after use for 25 to 30 years. The Scanning Electron Microscopy (SEM), X Ray Diffraction (XRD) and Energy Dispersive Analysis through X rays (EDAX) provide a very useful insight into the state of the conductor and gives important information to the strategic decision maker, whether or not to replace the conductor. It was observed in the present study that the zinc coating diffuses inside the steel strand under temperature and time effect. This unique study on the used conductors also reveals that the morphology of the coating and its interface structure changes significantly compared to an unused conductor of the same age.

***Keywords***: *Corrosion; Ultra High Strength Steel; Galvanization; Overhead Transmission Conductors.*

## 1. Introduction

The conductors used in high voltage transmission lines comprise of 20% to 30% of the total cost of the transmission line and pose as the critical part of the transmission line in terms of performance, useful life security and safety issues (Thrash R. *et al* 2007). Selection of the best conductor for a transmission line depends on several factors such as power requirements, terrain, ambient conditions, cost of conductor, supporting structure, governmental and environmental constraints. The most common types of overhead conductors are either composed of aluminum alloy strands wrapped around each other, e.g, All Aluminum Conductor (AAC) or All Aluminum Alloy Conductor (AAAC) or they are composed of Steel Reinforced Aluminum Strands (ACSR). The steel wire strand used to reinforce the conductor is typically composed of a high strength steel coated with zinc to provide a good corrosion resistance but possess poor conductivity. Over the years the high strength steel has been replaced by the ultra-high strength steel and the corrosion protection is enhanced by placing these strands at the inside of the conductor. Special grease is also used to avoid any water penetration towards these steel strands. The construction of an ACSR330 conductor which was investigated in this work is presented in Figure 1 and its properties are given in Table 1.

As can be understood, the integrity of the inner steel core wires is critical for the functioning of the conductor, which bear the weight of the conductor. These steel wires are galvanized and covered with grease for double protection against corrosion. Other major phenomena which can affect the properties of these steel wires is creep due to high temperature during the full loading and time effect. This can also create a longterm annealing effect which has been studied by other researchers (Hou X. *et al* 2013). ACSR type conductors' deterioration as a function of temperature is also studied by researchers (Lee D. D. *et al*, 2016, Lee D. D. *et al* 2011) where they discussed this problem under high heat conditions such as when forest fires take place in the vicinity of the high voltage lines. They reported that the galvanized steel wires faced melting of the surface zinc layer and eventually corrosion took place through atmosphere. Corrosion of galvanized steel wires for overhead high voltage conductors has also been a subject of investigation by researchers (Zhang J. K. *et al* 2010, Schwabe P. H., Pike D. 1988, Lyon S. B. *et al,* 1987). In their research, laboratory scale tests under accelerated environment containing NaCl solutions were conducted. The corrosion mechanism was found to be a mixed mode, including pitting, crevice and galvanic corrosion. Presence of sulphate ions in addition to the chloride ions in the environment is also observed to be a source of accelerated corrosion.

**Figure 1:** Cross section of the bundle conductor ACSR 330. The inner seven wires are made of ultra-high strength steel and outer 26 wires are made of high conductivity aluminum.

The conductor is manufactured under Japanese standards (JIS C-3110) and the specifications are summarized in Table 1, as provided by the manufacturer:

**Table 1:** General Specifications of the ACSR 330 conductor (JIS C-3110).

| | |
|---|---|
| Aluminum 26 Strands, | 4.0 mm diameter |
| Steel 7 Strands, | 3.1 mm diameter |
| Conductor Cross Section Area (Nominal) | 330 $mm^2$ Total 379.6 $mm^2$ |
| Conductor Diameter | 25.3mm |
| Conductor Specific Weight | 1.384kg/m |
| Coefficient of thermal Expansion (Eq) (Al = 23, Steel = 11.5) | 19 x $10^{-6}$ /C |
| Rated electrical resistance (maximum) | 0.088 Ω/km |
| Tensile Strength Steel wire | 1.86 GPa |

In the present work the ACSR 330 conductor microstructure of the 30 years old steel used wire is compared to the microstructure of the unused wire with same age. The state of zinc layer has been observed using Field Effect Scanning Electron Microscope (FESEM) and Energy Dispersive Analysis through X rays (EDAX). These results are further supported by X Ray Diffraction (XRD) and are reported in the results and discussion section.

## 2. Materials and Methods

The as received wires were cut into specimens of about 9 inches and cleaned from dirt and grease. On first visual inspection the grease on used conductors was much dry and black in color. Figure 2 shows the picture of inner structure as observed through naked eye.

Individual strands were cut in small pieces and cross section of steel strands were polished and observed by FESEM provided with EDAX (Schottky FE-SEM SU5000 Hitachi). The surface of steel strands was studied for corrosion products through XRD (Bruker D8 Advance).

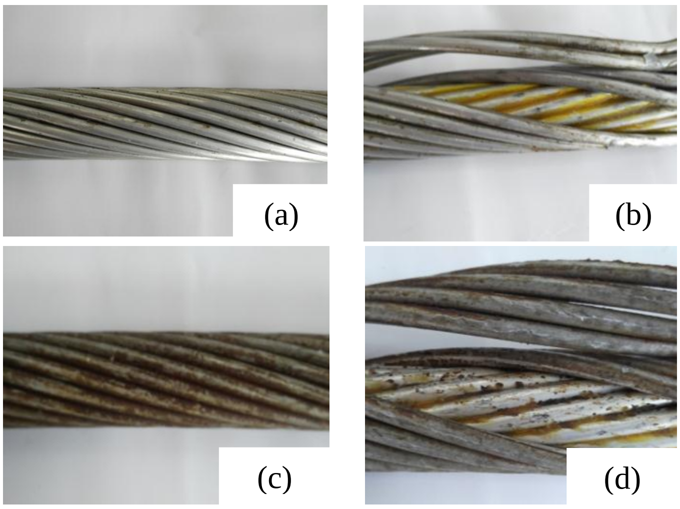



**Figure 2:** Outer construction of the ACSR conductor (unused (a) and used (c)). Aluminum strands are in spiral form. (b) and (d) show the status of inner layers. Degradation in the grease quality is obvious.

## 3. Results and Discussion

### 3.1 FE-SEM and EDAX

Figure 3 below presents an SEM image of polished steel strand from the ACSR330 conductor. This shows the state of zinc coating produced through galvanization on an unused conductor. The image has been taken by FE-SEM where the electron beam is produced through schottky effect Field Emission Gun. Such samples are very difficult to polish as the steel substrate is very strong and hard whereas the zinc coating is very soft. In order to obtain uniform polishing on both surfaces, it is very difficult to conduct polishing for a longer time, in detriment of polishing debris. The section is polished after mounting on a resin base. The resin debris can be seen accumulated on the coating edge due to its detachment from the mount. The image demonstrates a clean and smooth coating-steel interface, and the coating thickness is more or less uniform. The coating thickness varies between 42 to 45 µm.

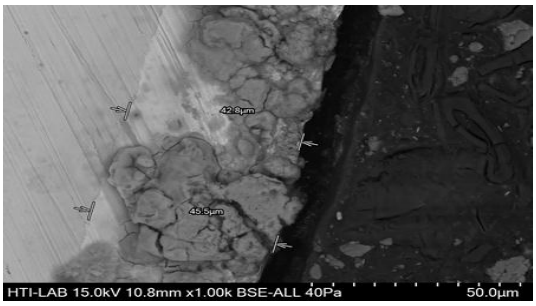
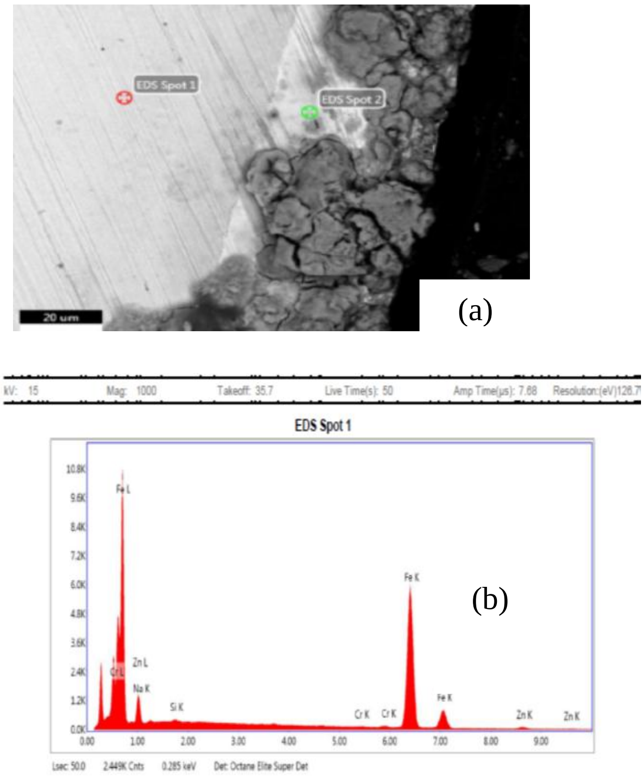



**Figure 3:** SEM image of polished surface of unused steel wire cross section.

Figures 4 (a), (b) and (c) show the spot EDAX analysis on the same image with precise spot position as indicated. It can be seen that the spot 1 is mainly composed of Fe with traces of chromium, carbon, Na and Zn (Figure 4 (b)). The presence of Zn at this spot can only be explained by the fact that during polishing, soft particles of zinc can detach and get deposited onto the steel surface. In Figure 4 (c) it is evident that the spot 2 is mainly composed of pure zinc.



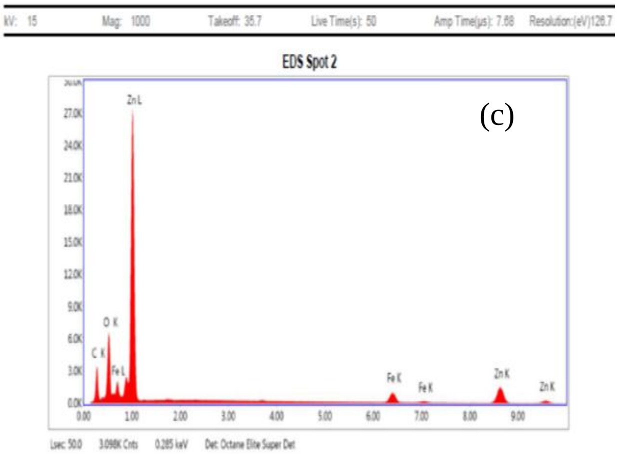



**Figure 4:** (a) SEM image of the polished surface of unused Steel wire cross section indicating the two spots of EDAX (b) Elemental spectra for spot 1 produced through EDAX (c) Elemental spectra for spot 2 produced through EDAX

Figure 5 reveals a very interesting micro structure. This is the SEM micrograph of the same galvanized steel strand but which has been in service for about 30 years. The high temperatures produced through thermal effect of high voltage and current combined with the time effect resulted in diffusion and counter diffusion of zinc coating into the steel conductor and diffusion of elements within steel into the zinc coating. The interface can be seen highly distorted and highly diffused, the coating thickness has changed, strikingly, the thickness has increased. This increase in thickness resulted in the dilution of zinc inside the coating.

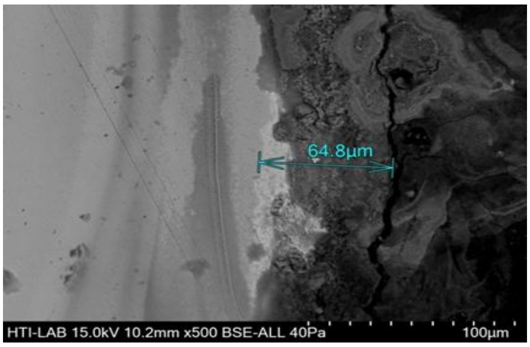



**Figure 5:** SEM image of the polished surface of used steel wire cross section.

Figure 6 presents the same polished surface under higher magnification and three areas are selected for Elemental analysis, Area 1, Area 2 and Area 3, represented by the red color rectangles. Area 1 is well inside the coating, Area 2 is between the coating and the substrate, whereas the area 3 is within the Steel substrate. The EDS results are shown under Figure 7 (a), (b) and (c). the Figure 7 demonstrates clearly that under the action of time, heat and cyclic stresses, the zinc has diffused into the steel. The coating thickness has now increased to about 65 microns at first sight, but actually, the zinc presence can be detected at a much longer distance into the steel core. The EDAX area scans give evidence that significant quantity of Zn has diffused into a distance of up to 130 µm into the steel boundary. Meanwhile Fe is also detected within Zn coating. This is a phenomenon produced as a result of counter diffusion of the two species, Fe and Zn.

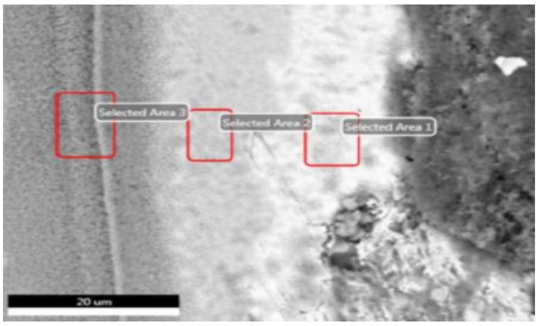



**Figure 6:** SEM image of the polished surface of used Steel wire cross section indicating the three selected areas for EDAX

One very interesting feature observed in Figures 6 and 7, where the diffusion of Zn appears to create bands of concentration in which the concentration of Zn appears to increase and decrease in a wave like fashion. A very similar phenomena is observed in mineral deposits, which occurs over a much longer period of time, named *Liesegang* bands after the famous scientist who discovered it in 1896. Several researchers have studied this phenomenon in minerals (Kulkarni S.D. *et al*, 2017, Rajurkar N. *et al,* 2015, George J. *et al,* 2005 and George J. *et al,* 2003) but in metals this phenomenon has not been studied so far.

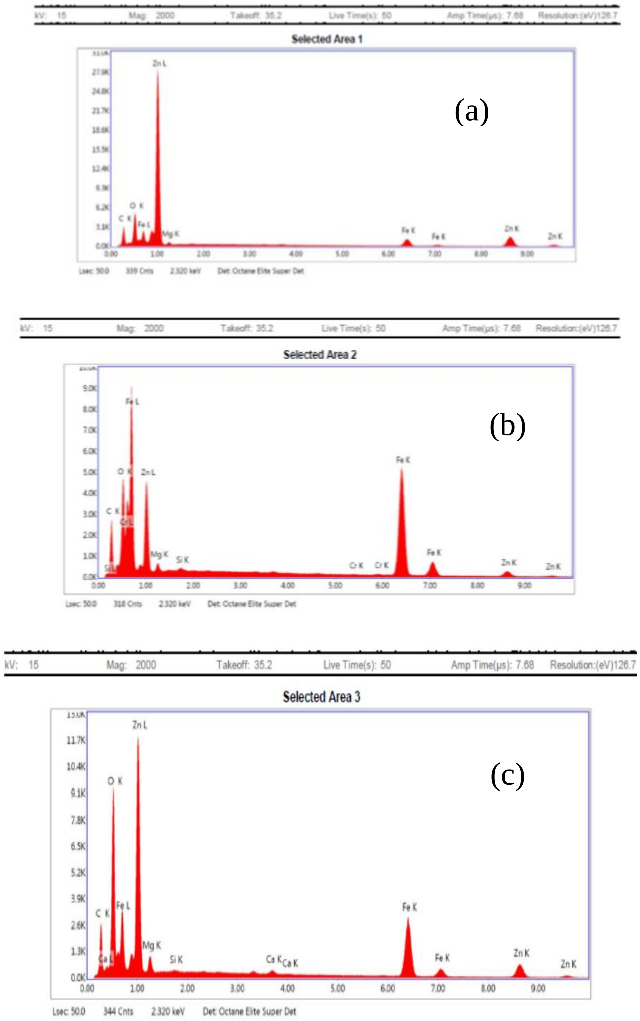



**Figure 7:** (a) Elemental spectra for Selected Area 1 produced through EDAX (b) Elemental spectra for Selected Area 2 produced through EDAX (c) Elemental spectra for Selected Area 3 produced through EDAX.

### 3.2 X Ray Diffraction (XRD)

X Ray Diffraction studies were conducted on the surface of the strands. This was done in order to verify if the corrosion has taken place on the surface of steel wires. Visual observation in Figure 2 (b) has indicated that the state of grease on the steel strands was not ideal. Some black spots were visible which could have prompted some corrosion. The results of XRD are presented in Figure 8 and Figure 9, for unused and used conductor steel strands, respectively.

Figure 8 shows that the surface coating on unused ACSR conductor steel wire contains 99.2% zinc. The zinc coating in this sample is almost unaffected as also demonstrated in EDAX results (Figures 4 (a), (b) and (c)). The total oxide content is less than 0.5%, which can be considered as negligible. On Figure 9 the XRD spectrum of used Steel wire surface is presented. In this figure the zinc content on the surface of the coating drops from 99.2 to 90%. There is presence Chromium Carbide (8.5%) which is believed to have diffused out of the steel core (Counter diffusion with Zn). This confirms the initial finding through FESEM and EDAX (Figures 7 (a), (b) and (c)) that Zn has migrated into the steel core and elements from steel have counter diffused towards outside surface. This has happened over a long period of 30 years of heating and cooling within acceptable temperatures. The total oxide found on the strand surface is less than 1%.

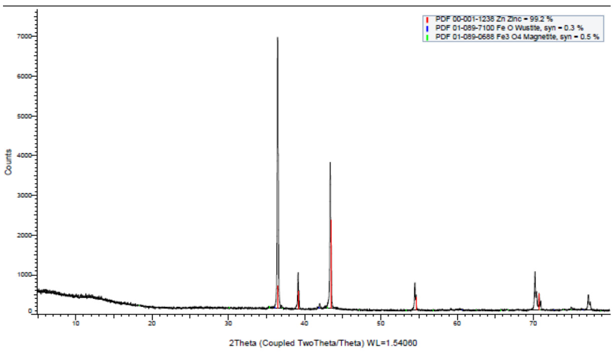



**Figure 8:** XRD patterns of the galvanized surface of unused steel wires from ACSR330 conductor.

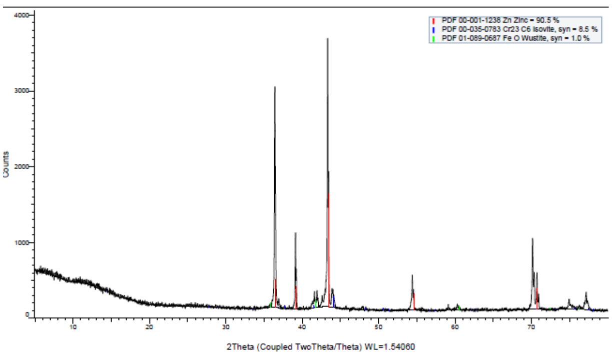



**Figure 9:** XRD patterns of the galvanized surface of used steel wires from ACSR330 conductor.

## 4. Conclusion

Upon visual inspection the grease on the outer layer for used conductor is relatively dry and dark spots are visible compared to the unused one. Further observation of the interior layer reveals that the grease exists but its quantity is less than the grease inside unused conductor. This is understandable as temperature changes and weather effect tends to degrade and contaminate the grease.

The FESEM analysis of steel strands in ACSR conductor confirms that the surface layer is composed of zinc. In the unused sample, this zinc layer is of uniform thickness, the thickness varies between 42 µm to 45 µm. The boundary between zinc layer and steel core is very sharp and clear. In the used steel wire, the zinc layer becomes discontinuous and diffuses into the steel. The diffusion of Zn appears to create bands of concentration in which the concentration of Zn appears to increase and decrease in a wave like fashion. The coating thickness increases to about 130 µm, the boundary between coating and steel core becomes diffused and discontinuous. The zinc content in the coating decreases, and there is outward diffusion of Cr observe. The same results have been verified through XRD.

## Acknowledgement

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