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# Failure analysis of wire-breaks in aluminum conductor production and investigation of early failure reasons for transmission lines

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ABSTRACT

In this study, continuous casting process performed using AA1070 and AA6101 feedstock alloys for bare conductor manufacturing. Test samples were provided at breaking time in casting and wire driving processes. Analysis of wire defects and damages were analyzed using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) and categorized with respect to fracture mechanism to investigate their possible origin. Seven different failure modes: hole defect, solidification cavities, tear apart of the embedded inclusions, "check" defect, a splinter from the embedded hard oxidized particles, overfill break, metal oxide accumulation zone breaks were detected on wire-break samples. This analysis was done to investigate early failure reasons of transmission lines due to working under several types of vibration phenomena in service life. It has been detected that major cause of the defects is related to the metal purification in the holding furnace. Besides, drawing die angles and guide of the stranding machines were also detected as another source of failure. The two main reasons for wire break were found as machine interaction and the inclusions.

## 1. Introduction

The stage of aerial bare conductor production includes casting and plastic deformation. The production starts with a melting of an ingot and casting of the feedstock at continuous casting unit. Then, wire drawing of feedstock is performed at any required diameter. Stranding of wires is the final process. When the conductor is a type of ACSR (Aluminum Conductor Steel Reinforced), aluminum wires are stranded onto reinforcing part composed of steel core of the conductor. When AAAC (All Aluminum Alloy Conductors) conductor types are manufactured, stranding process is performed using only EC grade aluminum wires with a combination of 1 + 6 + 12 + 18 etc. layers of wires [1–7]. Installation of aerial transmission line is a huge investment for the developing countries. Thus, most developing country governments challenge huge infrastructure investment. Therefore, countries expect long service life from the conductors. Nominal service life for the bare conductor is around 30 years and this very short period is not economically feasible for public investment [2–8]. Also, composite structures such as ACSR have low service life due to a galvanic action of the different material combinations. Al-Mg-Si alloy is a unique material with long-term service life for a conductor. However, Al-Mg-Si alloy conductor is an expensive product due to low production output. Moreover, life expectation of bare conductor depends not only on corrosion potential of metals but also processing quality due to metal-machine interactions. Service life of a conductor decreases

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because of environmental induced conditions: lightning strike, ice-shedding, oxidization, flashover, random vibration or galloping [7–14]. Additionally, if a wire has some damages and defects coming from processing of feedstock, service life is strictly affected by variable loads due to aerial vibrations. Micro defects and damages on a wire occur during the process steps from melting to tower installation [15]. When the previous statements are evaluated, main sources of failure in transmission lines can be divided into two groups: aeolian vibration and galvanic corrosion [16]. Vibration damages cause fatigue failures of aluminum strands at splices, clamps, and dampers. Maintenance can be required at any time during the life of a transmission line conductor. Reliability for a transmission line is defined as its ability to operate uninterrupted, safe and over a long period in a wide range of meteorological conditions. Conductors are the least understood components of an aging system but with continuing developments in sensors and data analysis. There is a cost and benefit to all transmission line maintenance work whether it is performed under live line working or offline working conditions [17]. Maintenance based life extension of structures have been carried out for many years. Maintenance methods and practices for a transmission line equipment are now well understood. Hardware and insulators can be replaced at once if necessary. The other deterioration source at transmission lines is galvanic corrosion. The corrosion resistance of a bare aluminum conductor for an overhead transmission line is very important when it is installed in such a corrosive district as a seashore, an industrial area, a salty desert or near a volcano, etc. There are two predominant corrosion mediums that attack ACSR, AAC conductors: a) industrial pollutant, b) marine atmosphere [18]. ACSR shows more complex corrosion mechanism compared to the AAC since it consists of galvanized steel strands and aluminum strands [19]. It has been shown by Harvard et al. [20] that atmospheric conditions have a significant effect on the corrosion rate of the aluminum conductors.

The aim of this study is to investigate early failure reasons for transmission lines regarding manufacturing defects in aluminum conductor production. During aluminum continuous casting and wire drawing process, fracture failure due to the defects in electrical conductor was investigated. In the section of "analysis of wire-breaks in aluminum conductor production", types of defects are described and failure analysis of the wires are presented. The root causes of the problem for preliminary investigation are mentioned in "conductor failure background" section. Under the heading of "aerial conductor production and experimental study", the type of the wire breaks has been analyzed in detail to find out of the fundamental sources of failure. Scanning electron microscope (SEM-Jeol 6060) and energy dispersive X-ray spectrometer (EDS) were carried out. Also, Shimadzu AG-X universal tensile test machine and GW Instek PPH 1503 linear DC power supplier were used to characterize the mechanical and electrical properties of the produced conductors.

## 2. Conductor failure background

Continuous vibration of an unprotected conductor may result in fatigue failures at a point of defect on an individual strand. Effects of vibration types on a conductor are given in Table 1 [21]. Wind motion causes repetitive bending and torsional stresses up to failure. Analysis of the growth of fatigue failure provides a considerable understanding of initial damages or initial defects. Close inspection of fatigue failures has shown that cracks begin at fretted regions including "defects or damages" where the strands have rubbed repeatedly against each other or against an armor rod or clamp. Micrographic studies show that the surface layer of a strand is severely disturbed by the fretting. Cracks appear within the disturbed layer, and they may penetrate undisturbed metal below fretted region [22]. The probable explanation of the phenomenon of fretting is as follows: Flexing of the conductor at the point of support results in a small amount of movement between adjacent strands in the conductor or between strands and adjacent members. At a microscopic level, the contact between metal surfaces is not a plane contact but rather a contact between asperities. The intimate contact between asperities, aided by the wiping action -which removes surface films- results in microscopic welds between the asperities. When movements between the strands surfaces are repeated for a long time, many welds are made and broken, and a

**Table 1**
Comparison of basic conductor motions [21].

| | Aeolian Vibration | Conductor Galloping | Wake induce Vibration |
|---|---|---|---|
| Affected overhead line types | All | All | All |
| Approx. frequency range (Hz) | 3 to 150 | 0.08 to 3 | 0.15 to 10 |
| Approx. range of Vibration amplitude (peak to peak) | 0.01 to 1 x d | 5 to 3000 x d | Rigid body mode: 0.50 to 20 x d |
| Weather condition favoring conductor motion: | | | |
| Wind character | Steady | Steady | Steady |
| Velocity (m/s.) | 1 to 7 | 7 to 8 | 4 to 18 |
| Conductor surface | Bare/Uniformly iced | Asymmetrically iced | Bare/Dry |
| Damage: | | | |
| Approx. time required for severe damage to develop | 3 months to 20 yrs. | 1 to 48 h. | 4 to 18 h. |
| Direct cause of damage | Metal fatigue due to cyclic loading | High dynamic loads | Conductor clashing accelerated wear in hardware |
| Line components most affected by damage | Conductor and shield wire strands | Conductor all hardware, insulators, structures. | Suspension hardware spacers, dampers, conductor strands |
| Design conditions affecting conductor motion | Line tension, conductor self-damping, use of dampers and armor rods. | Ratio of vertical natural frequencies to torsional natural frequencies, sag ratio and support conditions. | Sub-conductor-separation, tilt of bundle, sub-conductor- arrangement, sub-span staggering. |

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