25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1441
ALUMINUM ALLOY CONDUCTOR CABLE: FATIGUE AND FAILURE ANALYSIS

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Abstract. *The objective of this work is to generate experimental data to compare two types of All Aluminum Alloy Conductors ("A" and "B"), manufactured from the same material and, theoretically, submitted to the same heat treatment, with regard to their fatigue life and their failure. Wind-induced fatigue failure occurs with some regularity in conductors cables, causing loss of reliability in the electrical distribution system. A broken cable can result in significant damage to both the power company and its customers. A battery of eighteen fatigue tests was carried out in order to generate their S-N curves. The results showed that the fatigue life of cable "A" was around three times shorter than that of cable "B", with a higher dispersion of results. Cable "A" wires also exhibited lower hardness and tensile strength than cable "B" wires. Scanning electron microscopy analyses of fracture wires surfaces demonstrated that failures were caused by fretting fatigue. The lower hardening and tensile strength values of cable "A" wires compared to cable "B" cables are associated with supposed differences in the heat treatment process applied to each cable during manufacturing process. The heat treatment inefficiency led to the formation of fewer hardening precipitates, resulting in mechanical properties far from ideal, thereby shortening its fatigue life.*

Keywords: *Aluminum Conductor, Heat treatment, Fatigue, Failure Analysis*

1. INTRODUCTION

1.1 Fatigue

The appropriate design and maintenance of a cable are vital to the efficiency and durability of the overall electrical transmission system (Jorge and Hertwich, 2014). It is stipulated that the cost of the cables can be up to 40% of network capital investment total (Hingorani, 1995) (Jorge and Hertwich, 2014). They are submitted to electrical, mechanical and environmental loads during their service life, thereby requiring rigid control of manufacturing and maintenance processes. The performance of electrical transmission lines is directly related to the components characteristics, such as materials and heat treatments used in manufacturing (Wadell, 1991).

During their use, conductors cables suffer from damages caused, primarily by wind vibrations that significantly reduce their service life. The vortex promoted by the wind action can produce high-frequency vertical oscillations that can reach the resonance frequency (Aggarwal, Johns and Asbewsu, 2000) (Krueger et al., 2001). Such phenomena causes alternating bending stress in the cable's wires, which can generate fatigue/wear with a complete failure in the transmission lines, mainly at restricted movement points, such as dampers, suspension clamps, etc. (Zhou et al., 1996). These oscillatory movements promote slippage between wires and with contact points, which causes relative frictional forces leading to fretting between the components resulting in cable rupture in service (Fadel et al., 2012).

One way to characterize a conductor fatigue life is trough the S-N curve, which correlates the amount of cycles with the stresses it is submitted. The curve construction it is determined by fatigue specimens tests at a particular stress amplitude (σ), which remains constant during the entire assay, until failure occurs after a certain number of cycles (N). The process is repeated using others stresses, which will cause the sample to rupture with different lives, obtaining the curve σ -N (stress amplitude vs number of cycles), giving, that way, a good idea about the conductor fatigue behavior.

Due to the complexity of the structural cable configuration, mathematical expression was proposed by Poffenberger and Swart (Eq. 1), and its given the correlation between peak to peak displacement amplitude (Yb) of a region of the cable located at a standard distance, with dynamic bending stress (σa) at a point diametrically opposite to the last cable-clamp contact, Fig. 1 (Poffenberger and Swart, 1965).

$$\sigma a = K * Yb \tag{1}$$

where σa is the dynamic bending test (zero-to-peak), K the Poffenberger constant, the Yb displacement amplitude (peak-to-peak) of the conductor measured vertically at a point 89 mm from the last contact point

1.2 Aluminum Alloys and Heat Treatment

Aluminum alloys are used in engineering due their good industrial properties, such as low weight, high strength-to-weight ratio and corrosion resistance, in addition to their relatively low cost, high thermal and ease of manufacture. The mechanical properties of some of these alloys can be changed by the use of heat treatments based on phase solubility. Those treatments include precipitation hardening, consisting of solution and aging steps (natural or artificial) (ASM Handbook v.2, 2001). The 6xxx series contain magnesium and silicon, which, via solution treatment and aging, form the intermetallic rich in Mg-Si compound. To guarantee good mechanical performance, solution and precipitation treatments must produce a large amount of intermetallic compound uniformly distributed in the matrix, been able to blocking dislocation motion and increasing mechanical strength (ASM Handbook v.2, 2001) (ASM Handbook v.4, 1991).

During the aging process, supersaturation caused by the formation of a solid solution at the solution step declines gradually, leading to increased hardness when a high density of coherent and semi-coherent thin precipitates nucleate and grow in the aluminum matrix. Adequate control of the manufacturing processes and heat treatment parameters is critical in order to obtaining good mechanical properties.

1.3 Fretting

Wind vibrations promotes small movements in the cable wires when submitted to small-amplitude tangential oscillatory forces. Micro sliding zones emerge in these contact areas, giving rise to fretting fatigue (Lindley, 1997). The marks caused by wire/wire oscillatory contact, are high stress concentrators and propitious sites for fatigue crack nucleation (Azevedo *et al.*, 2009). A schematic diagram of the wire surface mark can be seen in the Fig. 2.

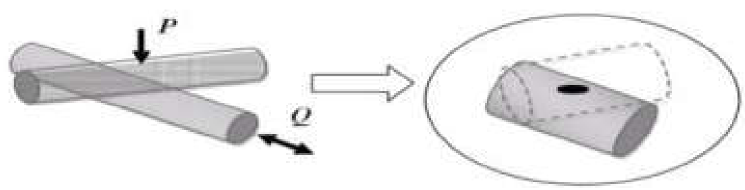

Figure 2. Schematic diagram of the wire surface mark (Azevedo *et al.*, 2009).

2. MATERIAL AND METHODOLOGY

2.1 Conductors Cables

AAAC (All Aluminum Alloy Conductor) conductors were tested in the present study. These consist of three (cable “A”) and four (cable “B”) concentric alternating strands of 6201-T81 aluminum wires, wound helically in opposite directions around a central wire. The schematic diagram of the arrangement of the strands in cables “A” and “B” is presented in Fig. 3.

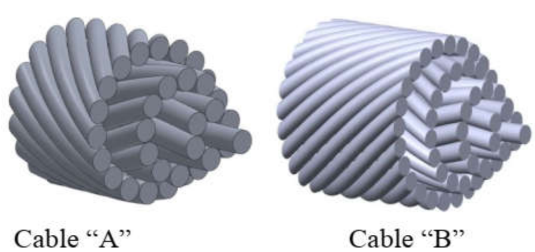

Figure 3. Schematic drawing with strands and wire orientation of the cables.

The conductor cables assessed here (“A” and “B”) were manufactured with wires made of the same aluminum alloy (6201) and theoretically submitted to the same heat treatment (T81). The chemical analyses of the wires of both cables are exhibited in Tab. 1, demonstrating that their chemical compositions are within specifications established for AA-6201 aluminum alloy. The same table shows the nominal composition described in the literature for this alloy.

Table 1. Chemical compositions of aluminum wires of cables “A” and “B” and nominal compositions of 6201 aluminum alloy (ASM Handbook v.2, 2001)[1].

Element [%]	Cable “B”	Cable “A”	Nominal[1]
Si	0.50	0.58	0.50 – 0.90
Fe	0.18	0.21	0.50 (max)
Mg	0.60	0.65	0.60 – 0.90
Cu	< 0.01	< 0.01	0.10 (max)
Al	Remainder	Remainder	Remainder

2.2 Conductor Cable Fatigue Tests

Nine samples of cable “A” and nine of cable “B” were used for the cable fatigue tests. These tests were carried out with 2144 H/w ratio, where H represents the horizontal tension applied to the cable during the fatigue test and w its linear density. The H/w parameter was selected instead of EDS (Every Day Stress) because in characterizing conductor fatigue, this parameter (H/w) considers the conductor diameter, which influences wind-induced energy and the frequency of vortex formation (Kalombo *et al.*, 2017).

The fatigue test adhered to the IEEE standard, and the failure criterion applied was the number of broken aluminum wires corresponding to 10% of the number of total aluminum wires in the conductor (IEEE, 2007 and CIGRÉ, 1979). Thus, failure occurs after ten per cent of the wires break.

2.3 Aluminum Wires Heat Treatment

In order to determine the influence of heat treatment on the mechanical properties of aluminum wires, solution and artificial aging were conducted with batches of cable wire samples exhibiting the shortest fatigue life (cable “A”). For these treatments, a Nabertherm oven with P310 controller was used. The samples were submitted to solution at a same temperature (520 °C). One of the sample batches did not undergo subsequent artificial aging. The samples of the other two batches were aged for different times (120 and 480 minutes), as described in Table 2. It is important to underscore that artificial aging occurred at the same temperature (170 °C).

Next, Vickers hardness was measured for the three batches, in order to determine the influence of aging time on hardness evolution.

Table 2. Temperatures and times used for heat treatments of wires of cable “A”.

Sample	Temp. Solubilization [°C]	Aging Time [min]
1	520	0
2	520	120
3	520	480

2.4 Failure Analysis and Mechanical Properties

The fracture surfaces of aluminum wires from cables “A” and “B”, ruptured in cable fatigue tests, were analyzed with field emission scanning electron microscope. To that end, secondary electron images revealed surface morphology. Surface failure images made it possible to establish the likely onset of the failure sequence, as well as the microscopic characteristics of mechanisms involved in the fracture of materials.

Uniaxial tensile tests were conducted on the aluminum wires of both cables using an MTS universal testing machine in order to determine the mechanical properties (tensile strength and Vickers hardness). The obtained stress- strain curves were used to determine the ultimate tensile strength of each wire. Vickers hardness tests were carried out on the aluminum wires removed from cables “A” and “B” as well as the samples of the three batches of heat treated wires. To that end, a Zwick/Roell universal microhardness tester equipped with a square-based diamond pyramid indenter and load of 5 kgf was used. For wires that were heat treated, average hardness reached in each batch of samples was calculated. At the end of testing, a comparative assessment of these mechanical properties was carried out.

3. RESULTS

3.1 Fatigue Tests and Mechanical Properties

Figure 4 shows the σ-N curves with fatigue test results of both cables ("A" and "B") submitted to the 2144 H/w ratio, in addition to the CIGRE Safe Border Line (CSBL) curve.

Despite being manufactured with the same alloy (Table 1), and theoretically submitted to identical heat treatments, cables "A" and "B" obtained different results in the fatigue tests. These results demonstrate that the difference in fatigue behavior between the two cables is not related to the H/w ratio used in the tests, but rather the different mechanical properties in each of the conductor cables, resulting in distinct microstructures depending on the methodology used in the manufacture of these cables.

Failure analyses detected fatigue fractures in both cables, but not enough to identify the causes of different performances. As such, uniaxial tensile tests and Vickers hardness were conducted in aluminum wires removed from both cables, in order to compare these mechanical properties. The results obtained in these tests (Tab. 3) revealed that cable "A" wires exhibited lower tensile strength and hardness than those observed in cable "B" wires.

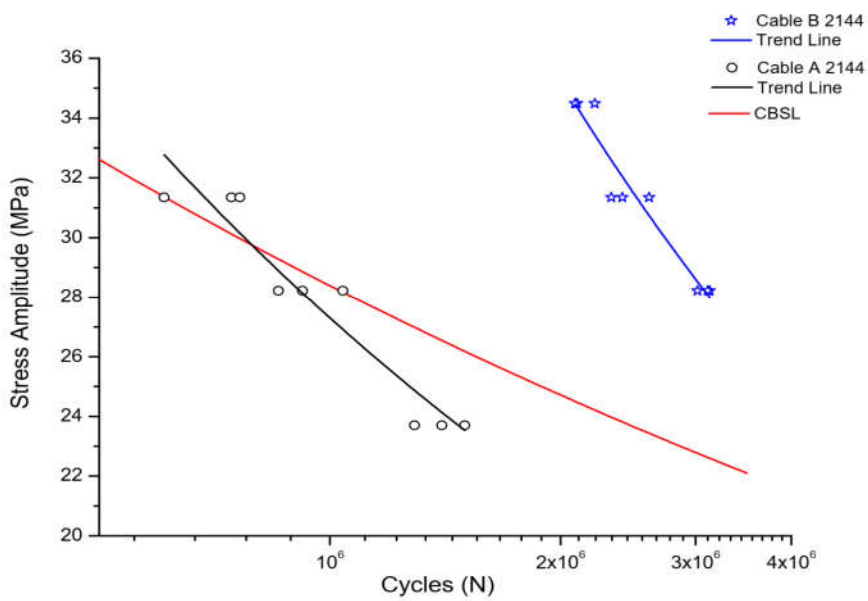

Figure 4. σ-N Curves of cables "A" and "B" tested under fatigue and the Curve Safe Border Line (CSBL).

Table 3. Mechanical properties of wires of cables "A" e "B".

Mechanical Properties	Wire of cable "A"	Wire of cable "B"
UTS [MPa]	309 ± 8,3	340 ± 17,2
Vickers Hardness [HV1]	90 ± 6,93	102,95 ± 1,41

The mechanical properties of aluminum are influenced by several factors, such as fine precipitates formed during aging treatment, which promote alloy hardness and impurities that can reduce mechanical properties, among others (Polmear ,1995). In order to determine the influence of heat treatment on the hardness of the alloy used to manufacture the cables, aluminum wires were removed from cable "A" and submitted to new heat treatments (solution at 520 0C and artificial aging at different times) and Vickers hardness tests. Average Vickers hardness values after three aging treatments are presented in Fig. 5.

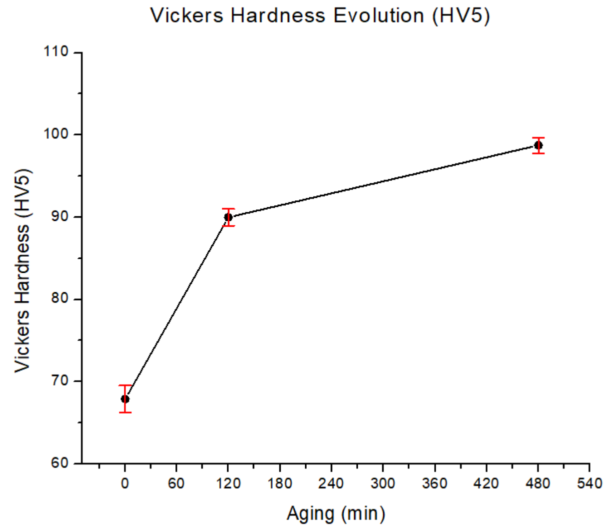

Figure 5. Evolution of Vickers hardness x aging time from cable "A" wires.

The results shown in Fig. 5 shows that solution treatment at the temperature of 520 °C of cable "A" wire with no subsequent aging caused a decline in the hardness of this 90 HV5 wire, as received, to 65 HV5. This result was expected, since solution promoted the dissolution of hardening elements in the matrix, leading to a solid solution with low hardness. The process requires temperatures slightly below the liquidus line and sufficient treatment time to completely dissolve the phases present in order to obtain a homogeneous solid solution. Adequate temperature selection is related to the composition of the alloy and the melting point of the intermetallic phases (ASM Handbook v.4, 1991) (Imam, Rahman and Khan, 2015).

Aging this wire for 480 minutes resulted in a considerable increase in hardness, reaching 98 HV, higher than its initial hardness value. This effect is related to the formation of the Mg-Si intermetallic compounds homogeneously distributed in the aluminum matrix, blocking dislocation motion and substantially increasing the hardness and tensile strength of the material. Earlier studies from (Imam, Rahman and Khan, 2015), (May et al., 2010), (Abreu et al., 2011) and (Ding, Biermann and Hartmann, 2002) established a correlation between an increase in hardness and the fatigue life of aluminum alloys.

During artificial aging, no allotropic transformation occurs in precipitation hardening. In this case, phase separation in solid solution occurs during aging. This heat treatment must be performed below the equilibrium solvus temperature and below the metastable miscibility gap, that is, the Guinier-Preston zone (ASM Handbook v.4, 1991) (Polmear, 1995) (Iman, Rahman and Khan, 2015).

3.2 Failure Analysis

In both cables wire failures started in the wire-wire contact regions, causing fretting marks during oscillatory movement over the course of the fatigue test, as shown in Fig. 6a. Figure 6b shows the fracture surface of aluminum wire from cable A, with the fracture initiation (1), beach marks (2) and the ductile final fracture (3).

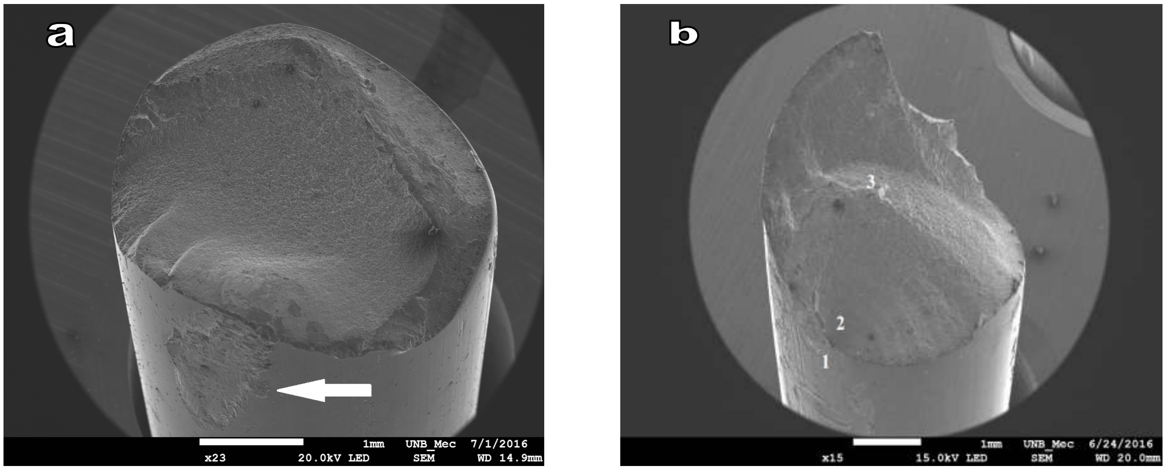

Figure 6. SEM image of fretting fatigue crack origin of conductor “B”, indicated by the arrow (left) and fracture surface of aluminum wire of cable “A” showing fatigue fracture regions (right).

Fretting fatigue marks cause cracks to spread to an area transverse to the longitudinal axis of the applied load (ASM Handbook v.11, 2002). This crack mechanism can be seen, and confirmed, by the beach marks (pointed by the white arrow), which is observed in the fractured wire sample from cable “A” (Fig. 7).

Figure 7. Surface fracture detail from a cable “A” wire.

Figure 8 shows the fracture of the aluminum cable “B” wire and, as seen for cable “A” wires, the 3 fatigue characteristics regions can be identified. The crack initiation (1), followed by the fatigue propagation (2). Some beach marks can be seen, white arrow.

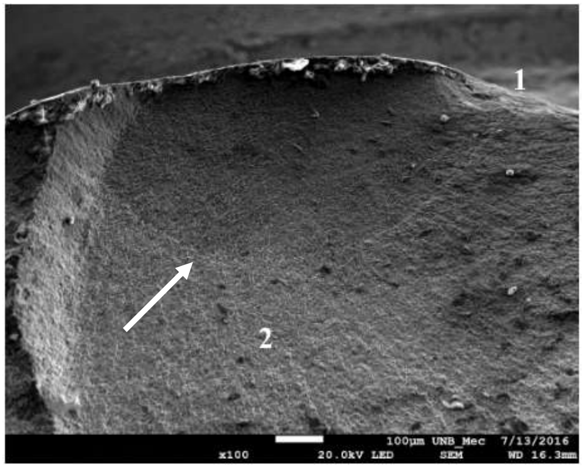

Figure 8. Fracture surface from cable “B” wire showing crack origin (1) and fatigue prapagation (2).

The wire’s final fracture regions exhibited dimples, which is a characteristic of the ductile fracture mechanism (Fig. 9).

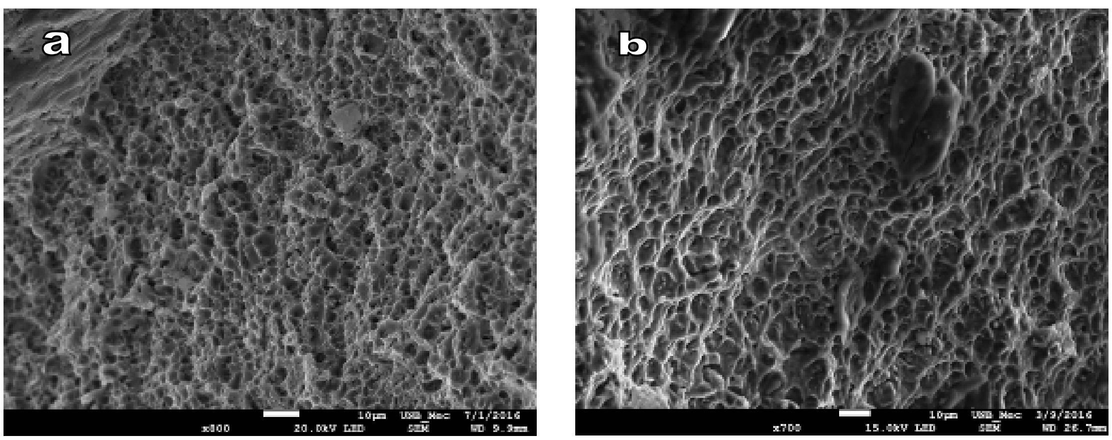

Figure 9. Final Region of fracture surface showing equiaxial dimples. (a) Cable “A” wire and (b) cable “B” wire.

4. CONCLUSIONS

The fatigue tests conducted with the same parameters in two conductor cables (“A” and “B”) made of the same 6201 aluminum alloy and, theoretically, submitted to the same T81 heat treatment exhibited markedly different fatigue lives, resulting in premature failure of cable “A”. Based on the chemical, mechanical and microstructural analyses carried out on wires removed from the above-mentioned cables, we concluded the following:

- The fatigue life of cable “A” was around three times shorter than that observed for cable “B”, in some cases below the safety curve proposed by CIGRE (CSBL).
- Surface fracture analyses using scanning electron microscopy demonstrated that both wires displayed the three regions characteristic of fatigue failure, starting in the wire-wire contact region, spreading by fretting fatigue and final ductile fracture, indicating predominance of multiaxial stresses at the end of the process.
- Cable “A” wires showed worse performance in hardness and tensile strength when compared to cable “B” wires. This performance is strongly correlated with possible differences in the heat treatments applied to the two conductors, given the similar chemical composition of the aluminum wires used in their manufacture. A supplementary artificial aging treatment for the cable “A” wires resulted in increased hardness, demonstrating the influence of this heat treatment on the mechanical properties of this alloy.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of TBE, within the scope of ANEEL R&D. The support of Finatec is also acknowledge.

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