THE RESEARCHES OF INFLUENCE OF STRENGTHENING ON FATIGUE STRENGTH OF EN AW-1370 AND Cu-ETP WIRES

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Abstract

The subject of the paper concerns fatigue strength tests of aluminum and copper wires in different state of strain hardening used in overhead power lines and railway power lines. The paper attempts to describe operating problems, especially fatigue strength, research methodology, description of a research stand. Based on study results and their analysis, conclusions were formulated concerning the differentiation of fatigue strength of Cu-ETP and EN AW-1370 wires.

Keywords: Fatigue strength, S-N curves, Whöler's curves, fatigue fracture, wire EN AW-1370, wire Cu-ETP

1. INTRODUCTION

The traditional ACSR (Aluminum Conductor Steel Reinforced) overhead wires are made from a high strength steel core and several layers of reinforced aluminum wires forming the electrically active part of the conductor. Operating conditions, and the work under variable stress derived from von Karman vortices in particular, leads to fatigue cracking of the outer layer of wires, first of the outer layer, and then the inner layers [1]. Von Karman vortices are created as a result of detaching of a laminar jet of wind flowing over the wire, and cause its vibration called wind, or aeolian [1-2].

The dynamic component of tension, dependent on the static tension of the wire, its geometric construction and rigidity (the number and diameter of the wires, the coil angle), lead to fatigue destruction of the wires during overhead operation. The consequence of this is the gradual degradation of the cable as a whole, which is a decrease in the electrically active cross-section, and as a result of overheating, also in its mechanical properties. The ultimate effect is breaking of the cable and a fault of the line. A passive method of counteracting the effects of aeolian vibration is to reduce the stress tension of the cable, which is usually impossible, or very limited, due to the overhang of the cable. The active method of counteracting the effects of aeolian vibration is the use of dampers designed to dissipate the energy of aeolian vibration. For several years now, the currently binding normalization in the design of high voltage overhead power lines imposes a requirement of a 50-year failure-free exploitation. This translates into increased parameter requirements for materials used to build the line in general, and in particular for the construction of conductors. Examples of a fatigue-damaged aluminum and copper conductors are shown in **Figure 1**.

Figure 2 shows S-N curves, i.e. the dependence of the values of the alternating stress amplitude on the number of cycles that are the accepted and recognized method of assessing the fatigue resistance of materials [3]. Curves 4 and 3 refer to wires (4 - AlMgSi alloy, 3 - Al alloy), the hatched box 3 - to wires, and the bottom line 1 is the so-called safe base line (SBL), as determined by the CIGRE (International Council on Large Electric System). As noted, compared to conductors, wires withstand several times higher stresses until fatigue destruction (with the same number of vibration cycles). The lower position of S-N curves for cables stems precisely from cyclical slippage, continuous refreshing and oxidation of the contact surface of vibrating wires in both layers and between the layers. To put it differently, at the same amplitude of the alternating tension, cables are destroyed by fatigue in a significantly lower number of cycles than individual wires of which the cable is made.

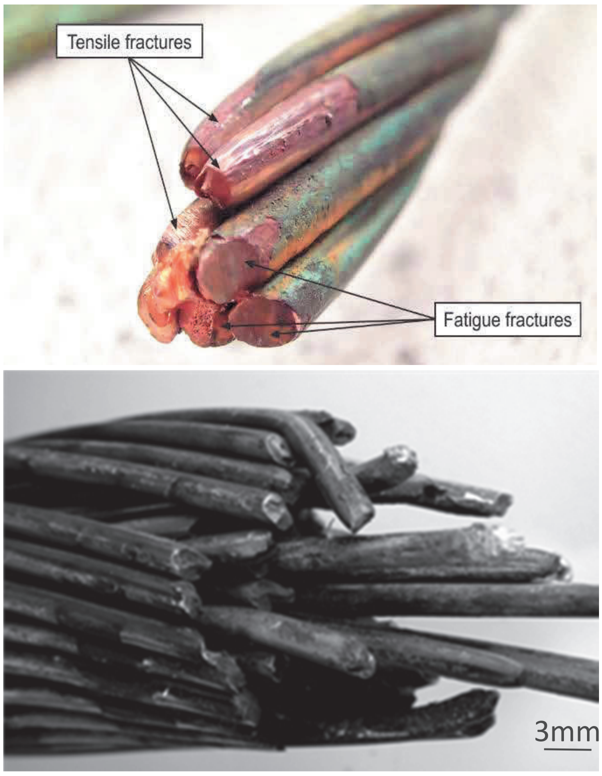

Figure 1 Fatigue failures of cooper conductor (upper) and aluminum conductor (bottom)

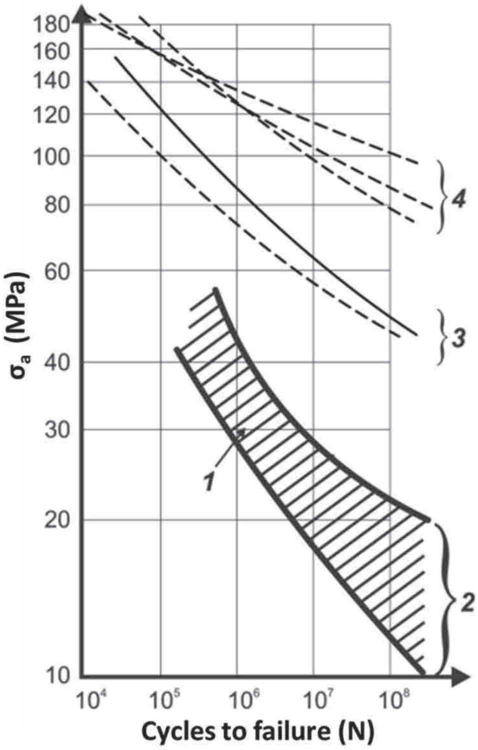

Figure 2 Stress-number of cycles to failure curves, 1- CIGRE SBL - safe border line; 2 - conductors; 3-aluminum wires; 4 - Al-Mg-Si wires [2]

Fatigue damage occurs in any material, if a combination of static and dynamic stress exceeds the fatigue strength of the loaded material. In the case of conductor, shock load includes axial and radial normal stresses, as well as bending, shear and torsion stresses. Thus, the transferable no-damage number of load cycles depends on the value of static load, dynamic stress amplitude and intensity of fretting corrosion. Analysis of the conductors fatigue characteristics reveals that the number of cycles until destruction is inversely proportional to the breaking stress. The aim of this work is to show differences between aluminum and copper wires in different state of strain hardening used in overhead power lines and railway power lines. [3-5].

2. OBJECTIVE, PROGRAM, RESEARCH METHODOLOGY

The aim of the study is to evaluate the fatigue strength of wires grade EN AW-1370 in various temper, used in overhead power lines and copper wires grade ETP in various temper- used primarily as railway traction conductors. **Table 1** shows the mechanical properties of wires selected for testing.

Table 1 Mechanical properties of wires selected for testing, EN AW- 1370 and Cu-ETP

Material	Degree of hardening	Diameter (mm)	UTS (MPa)	Proof stress (MPa)
EN AW 1370	90%	3.00	166	152
EN AW 1370	12%	3.00	80	71
Cu-ETP	86%	3.00	433	413
Cu-ETP	11%	3.00	257	158

Wires with a base of approx. 40 cm were cyclically subjected to rotational bending until they were destroyed. **Figure 3** shows the layout of the stand, and **Figure 4** - a photo of the stand. The nature of the rotary-flexure stand for the fatigue testing involves generating a variable strain in the test wire by means of bending the sample and then rotating it (3000 rpm). Stress in the presented stand is transmitted by symmetrical deflection of the sample by a known deflection vector (0÷230 mm with a step change every 10 mm).

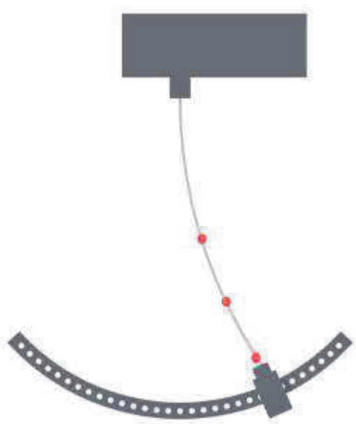

Figure 3 Scheme of fatigue stand [2]

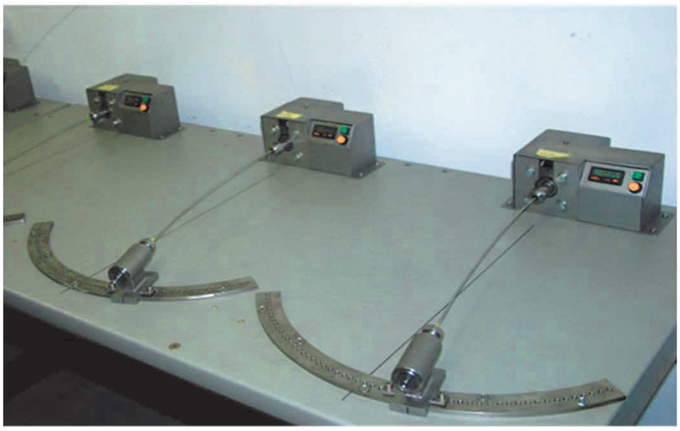

Figure 4 Fatigue strength wires stand

The study was performed under stresses, the values of which are shown in **Table 2**.

Table 2 Values of stress used for obtaining of Wöhler's curves

Material	**Stress** (MPa)								
EN AW -1370	135	120	105	90	75	60	45	30	15
Cu-ETP	344	295	246	224	197	149	124	100	75

The obtained research results allowed the development of Wöhler's curves as a function of stress and the number of cycles until destruction.

3. STUDY RESULTS AND THEIR ANALYSIS

Based on the fatigue tests conducted, the results were developed for the stress dependence on the number of cycles until failure the selected wires EN AW-1370 and Cu-ETP. **Figures 5-8** show the Wöhler's curves chosen for wire testing.

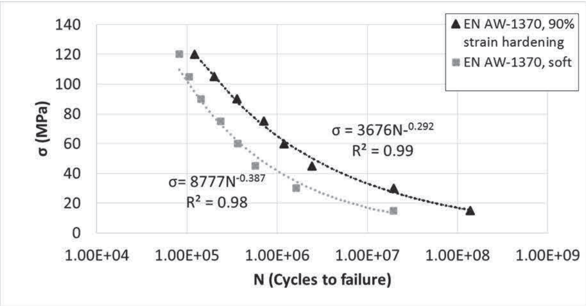

Figure 5 Characteristics of stress as a function of the number of cycles to failure - EN AW -1370 wires with different temper

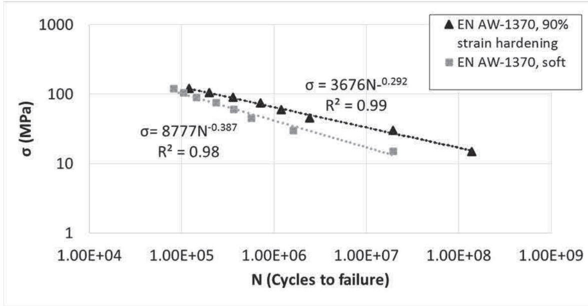

Figure 6 Characteristics of stress as a function of the number of cycles to failure - EN AW -1370 wires with different temper - logarithmic scale

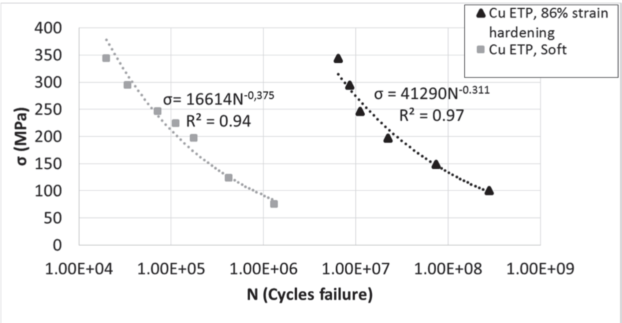

Figure 7 Characteristics of stress as a function of the number of cycles to failure - Cu-ETP wires with different temper

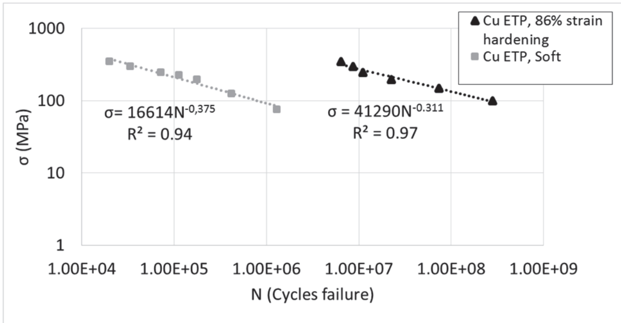

Figure 8 Characteristics of stress as a function of the number of cycles to failure - Cu-ETP wires with different temper - logarithmic scale

The developed S-N curves were described by equation (1), which is relation between stress and number of cycles to failure:

$$\sigma = k\left(N\right)^{n} \qquad (1)$$

in which:

σ - stress (MPa),

N - number of cycles to failure,

k, n - materials factors.

The proff of the correct approximation is fact that aluminum and copper fatigue curves are linear in logarithmic scale (see **Figures 6** and **8**). In the **Table 3** were presented mechanical properties of tested wires and values of materials coefficients n i k according the equation no 1.

Table 3 Values of materials factors of Cu-ETP and EN AW-1370 wires S-N curves

Material	Degree of hardening	Diameter (mm)	UTS (MPa)	Proof stress (MPa)	Linear factor *k*	Power factor *n*
EN AW -1370	90%	3.0	166	152	3676	-0.292
EN AW -1370	12%	3.0	80	71	8777	-0.387
Cu-ETP	86%	3.0	433	413	41290	-0.311
Cu-ETP	11%	3.0	257	158	16614	-0.375

Figures 5 - 8 show that the curves representing aluminum wires and copper wires in the hardened temper are higher and what's more, they are located to the right in the relation to the curves representing soft temper of wires. Values of linear coefficients k and power coefficients are higher for wires in hard temper both for aluminum and copper. This situation means that hardened wires are more fatigue strength for the same level of stress than soft wires. This observation is compatible with the common knowledge about the influence of material strength on his fatigue strength. Detailed analysis shows that in the case of aluminum the difference of fatigue strength for the same stress between soft and hard temper wires is twice less than in the copper. Interesting question is about reasons of this situation. For both aluminum and copper wires the difference in strain hardening is on the same level - approximately 90%. The fundamental difference between the materials lies in microstructures. On the **Figures 11** and **12** are shown microstructure of aluminum and copper wires in hard temper. In case of copper wire we observe the more fine-grained microstructure than in the aluminum wire.

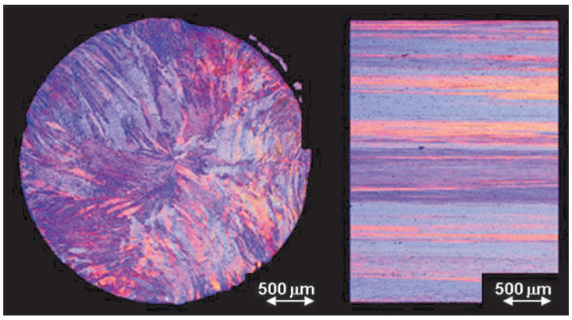

Figure 9 Microstructure of aluminum wires (hard temper), optical microscopy

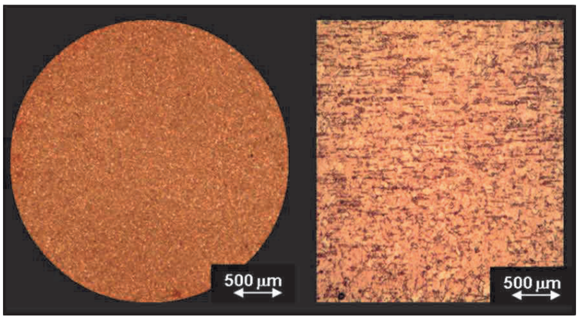

Figure 10 Microstructure of copper wire (hard temper), optical microscopy

In order to compare the "one to one" fatigue strength of copper and aluminum, the relationship between the number of cycles to failure and the effort of both materials was developed. The effort criterion is defined by the following equation:

$$W = \frac{\sigma}{PS} \cdot 100\% \qquad (2)$$

in which:

- W - effort
- σ - stress during the fatigue test
- PS - proof stress

Figures 11 and **12** show relationships between effort and number of cycles to failure of both materials.

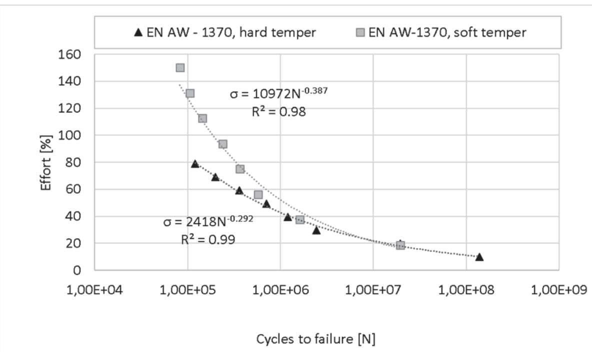

Figure 11 Characteristics of effort as a function of the number of cycles to failure - EN AW-1370 wires with different temper

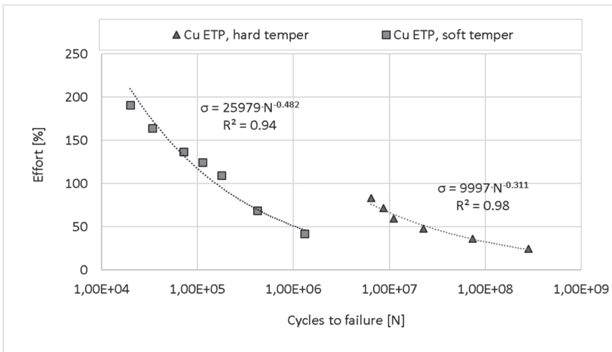

Figure 12 Characteristics of effort as a function of the number of cycles to failure - Cu-ETP wires with different temper

Detailed analysis of graphs on the **Figures 11** and 12 show difference between aluminum and copper fatigue strength directly. In case of copper (Figure **12**) difference between fatigue strength of hard and soft wires is constant for every effort level, while in case of aluminum it is dependent on the effort level. For effort level below 30% curves are overlapping (see **Figure 11**). This means that in case of aluminum temper of the wires has a negligible effect on high cycles fatigue strength (> 10^7 number of cycles).

4. CONLUSION

Based on the results of the experimental studies, it can be stated that:

1) The fatigue strength for both aluminum and copper wires can be described by the power relationship in the layout stress-number of cycles to failure.
2) Both materials fatigue curves are linear in logarithmic scale.
3) The same level of stress for copper wires results in longer operating times than for aluminum wires, regardless of the kind of temper.
4) The main reasons of copper and aluminum wires fatigue strength difference is microstructure (size of grains).
5) The evaluation of copper fatigue strength using the effort criterion leads to the same conclusions as in the criterion using the stress values expressed in MPa, while in case of aluminum temper of the wires has a negligible effect on high cycles fatigue strength (> 10^7 number of cycles).

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