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COMPARATIVE STUDY OF DAMAGE ANALYSIS AND LIFE PREDICTION OF ELECTRICAL CABLES IN OVERHEAD DISTRIBUTION NETWORKS - APPLICATION TO COPPER AND ALUMINUM CONDUCTORS

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Abstract- The use of copper and aluminum electrical wires is indispensable in all fields, which requires the obligation of their characterization and the analysis of their mechanical behavior. Therefore, the purpose of this document is to carry out an experimental study on a number of samples of copper and aluminum power transmission wires in order to define their behavior. To this end, a set of tensile tests and experiments are carried out on several specimens, then a statistical approach adopted to analyze the results obtained based on a (student) statistic to treat the reliability and another (Weibull) statistic to treat the failure and damage. Finally, a comparative study of the two types of electrical wires (copper and aluminum) is carried out to examine the various advantages and disadvantages of each type.

Keywords: Electrical Wire, Mechanical Behavior, Weibull Law, Student Law, Reliability, Tensile Test, Damage.

1. INTRODUCTION

Copper and aluminum are the most used conductive materials for power transmission cables due to their best technical characteristics both in terms of mechanical resistance and conductivity. Also, the ductility of these materials allows them to resist several mechanical and environmental phenomena, things that give them a high priority of use for various applications and large investment facilities, including overhead and underground electrical transmissions [1, 3].

Generally, in front of several defects and problems in these furnaces, during their production, during their installation and during their use because of high power consumption, aging, high loads and harsh environments. This necessarily requires tests (mechanical, electrical, ...), and detailed studies. In order to choose a good material before its use, and define its reliability, predict its life and also estimate its evolution over time, in order to be able to perform preventive maintenance of the systems in which it is used, and have the possibility to implement an adequate strategy based on problem solving and find practical and decisive ideas with reasonable costs, to prohibit any adverse effects of their failure and any significant damage that may lead to catastrophic results [4, 11]. Several scientific researches, experimental and theoretical works have been carried out to study copper and aluminum electric cables. We can refer mainly to the work of Ouaomar, et al. [12]. This work is based mainly on the performance of purely experimental tests on copper and aluminum wires and compared their results with those of the literature.

2. EXPERIMENTAL TRIALS

This section focuses on chemical and mechanical characterizations performed on aluminum wire samples taken from power transmission cables [13, 15]. The copper wires chosen to perform this comparison are already studied and are of type H 07 V-H [13]. The aluminum wires under study are of type U 1000 ARVFV. Figure 1 shows a sample of the aluminum wire used in this study.

Figure 1. Aluminum wire sample

We performed a spectrometric analysis of the aluminum wires, using an AMETEK spectrometer, in order to determine their chemical compositions and especially the percentage of aluminum which is the most important element in the composition of the electric wire alloy. Table 1 represents the results obtained.

Table 1. Chemical composition of an aluminum wire

Sn (%)	Cd (%)	Mg (%)	V (%)	Sr (%)
0.361	0.294	0.075	0.037	0.145
Cu (%)	Fe (%)	Si (%)	Al (%)	Cu (%)
0.134	0.785	2.05	94.9	0.134

The result obtained represents a satisfactory percentage of 94.9% (Al), which confirms the authorization to perform mechanical tests on these wires to define their mechanical characteristics, so to carry out this study in compliance with the operating mode and the procedure of the tensile tests we adopted the norms and standards of tensile strength of electrical cables.

The specimens studied are prepared according to the standards with a number of 16 samples, they have a length of 200 mm and a diameter of 1.8 mm. The tensile tests were performed using a ZwickRoell tensile testing machine with a capacity of 2.5 KN. After mounting and securing the specimens to the machine jaws, the tests were initiated with a 2 mm/min rise rate setting according to the standard.

3. RESULTS AND DISCUSSION

The set of tensile tests performed on the aluminum wire specimens, allowed to draw the curves that represent the stresses as a function of the deformation as shown in Figure 2, then conclude their mechanical characteristics.

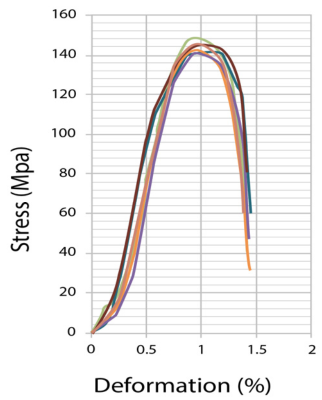

Figure 2. Stress-strain curve of aluminum wire

Table 2 represents the results obtained from the tensile curves of the aluminum wire, where, E is Young's module, σ_e is Elastic limit, σ_r is Breaking strength and ε is Deformation.

Table 2. Mechanical properties of aluminum specimens

E (MPa)	σ_e (MPa)	σ_r (MPa)	ε (%)
75	135	142	1.4

A student's statistical study is applied on the results presented in Table 3 which are obtained from the elastic and maximum limits of our mechanical characterization, in order to define the confidence intervals of the stresses by calculating the large and small limits of the average stress [16, 17]. Student's law is described by Equation (1).

$$P\left[-t(\alpha,\mu) \le \frac{X-\mu}{\frac{S}{\sqrt{n}}} < +t(\alpha,\mu)\right] = 1-\alpha \tag{1}$$

where,
X: Average of the maximum stresses of the different specimens
n: Number of specimens
μ': $n-1$
S: Standard deviation
α: Risk threshold
t (α, μ): Value given by the table annexed to Student

Table 3. Results of elastic limits and maximum stresses of aluminum wires

Trial N°	Elastic Limit [MPa]	Maximum Stress [MPa]
1	133	142
2	133	142
3	130	140
4	133	141
5	135	144
6	132	142
7	136	147
8	136	145
9	136	144
10	133	143
11	133	141
12	136	145
13	136	147
14	137	146
15	138	145
16	133	143
Average	134.375	143.563
Standard Deviation	2.20	2.193

From Equation (1), we define the probability limits μ by:

$$P\left[X-t(\alpha,\mu);\alpha\frac{s}{\sqrt{n}} \le \mu < X+t(\alpha,\mu);\alpha\frac{s}{\sqrt{n}}\right] = 1-\alpha \tag{2}$$

- The elastic limit of electrical wires:

- Copper [13]:

$$\mu_{elastic} = 165.68 \pm 2.13\frac{2.36}{\sqrt{16}} = [164.43;167\text{MPa}]$$

- Aluminum:

$$\mu_{elastic} = 134.375 \pm 2.13\frac{2.20}{\sqrt{16}} = [133;136\text{MPa}]$$

- The maximum stress of the electrical wires:

- Copper [13]:

$$\mu_{\max} = 218.37 \pm 2.13\frac{1.48}{\sqrt{16}} = [217;219\text{MPa}]$$

- Aluminum:

$$\mu_{\max} = 143.563 \pm 2.13\frac{2.19}{\sqrt{16}} = [142;145\text{MPa}]$$

We have defined the confidence intervals from which the results of the constraints obtained with a probability of 95% can be found. Therefore, all the values which are in these intervals are accepted and conform.

Also, another statistical analysis of Weibull is adopted to determine the maximum stresses that can be applied to this material with a probability of failure below 1%. And subsequently an estimate of the probability of survival (reliability), and the probability of damage (failure) [18, 19]. Knowing that this law is described by Equation (3):

$$P_s = e^{-(\frac{\sigma}{\sigma_0})^m} \quad (3)$$

where,

P_s: Probability of survival

σ: The applied stress

σ_0: Scaling parameter

m: Weibull modulus (dimensionless)

Knowing that the points of the Weibull curve follow a linear distribution such that.

$$\ln(\ln(\frac{1}{P_s})) = m(\ln(\sigma) - \ln(\sigma_0)) \quad (4)$$

The MINITAB software was used to find the parameters of this equation.

3.1. The Limit of Elasticity of Aluminum Wire

We used the MINITAB software to find the necessary parameters of the Weibull distribution as Figure 3.

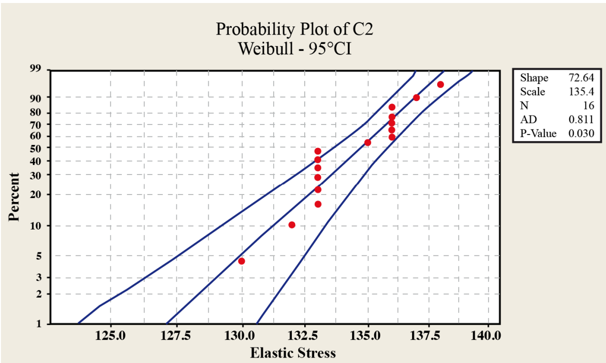

Figure 3. Weibull parameters by Minitab software

From the obtained Weibull parameters we determined the equation of the regression line of Equation (5).

$$Y_{elastic} = 72.64x - 135.4 \quad (5)$$

Using this equation, a model of the survival probability Ps and its inverse the failure probability P_s was determined knowing that ($P_s + P_f = 1$) as shown in Figure 4.

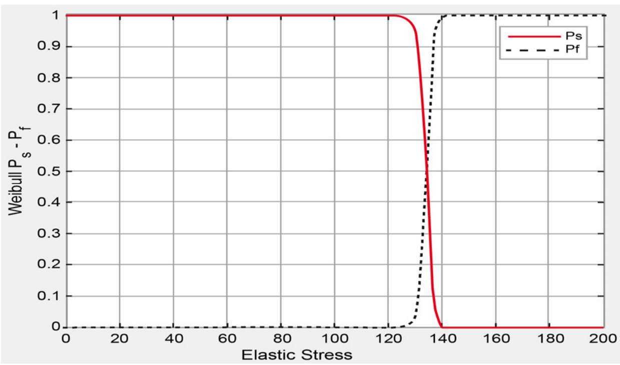

Figure 4. The probability of fracture and survivability as a function of yield strength

3.2. Maximum Stress of Aluminum Wire

To define the Weibull parameters of the maximum stresses, we continued the same way used in the elastic stresses. Figure 5 shows the curves and the results obtained.

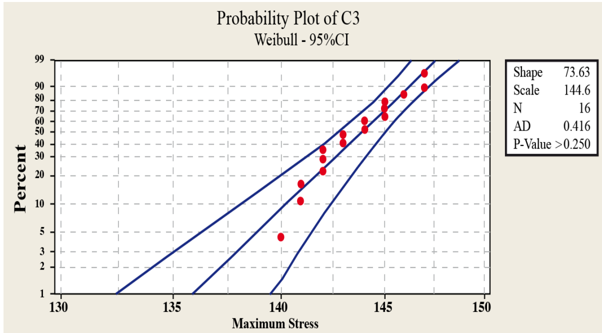

Figure 5. Weibull parameters by Minitab software

From Figure 5, an equation of the regression line was determined as Equation (6).

$$Y_{max} = 73.83x - 144.6 \quad (6)$$

Subsequently, a modeling of the survival probability P_s using Equation 6 to plot its curve as a function of its inverse the failure probability curve P_f as Figure 6.

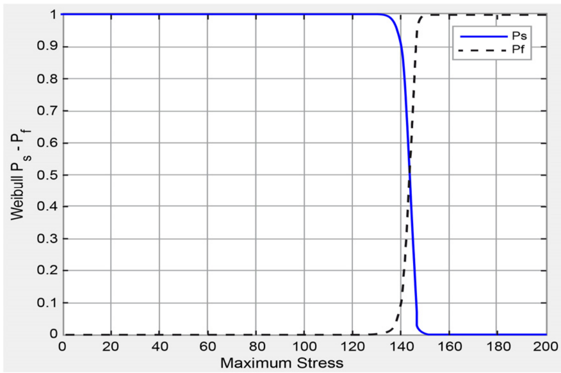

Figure 6. The probability of survival and failure as a function of maximum stress

Finally, a combination is made on the two curves of Figures 4 and 6 of elastic and maximum stresses of aluminum wires as shown in Figure 7, to make a comparison with those of copper wires.

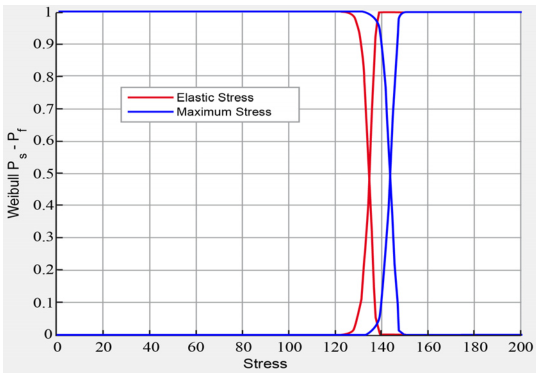

Figure 7. The superposition of the survival and failure probability curves for aluminum wire stresses

Figure 8 shows the reliability and failure estimation curves represented by the set of stresses obtained during the tests applied on the copper wires [13].

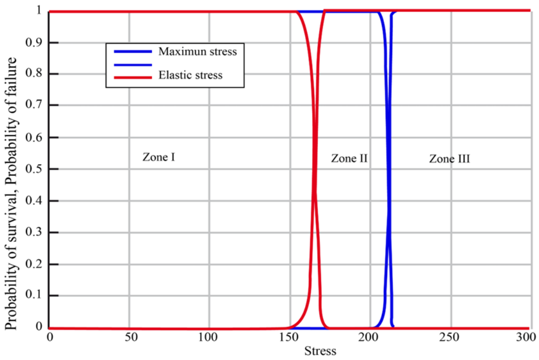

Figure 8. The superposition of survival and failure probability curves of elastic stress and maximum copper wire stress [13]

According to Figures 7 and 8, it can be seen that the points of intersection of the survival probability and failure probability curves as a function of copper wires stress are higher than those of the aluminum wires. This indicates that the aluminum wires have a lower life span than the copper ones.

4. CONCLUSION

Statistical studies performed on the different specimens of aluminum and copper wires showed that the maximum stress of copper wires is significantly higher than that of aluminum ($\sigma_{u,\mathrm{Cu}} = 218$ MPa, $\sigma_{u,\mathrm{Al}} = 143$ MPa). Copper wires can withstand more mechanical loads compared to aluminum wires. On the other hand, the Weibull reliability study performed on the maximum stresses revealed a low Weibull modulus for both aluminum and copper electrical wires, it can be concluded that the defect distribution is very heterogeneous. It should also be noted that the modulus of copper is lower than that of aluminum. This allows us to say that the heterogeneity of the distribution of defects in aluminum is relatively higher than that of copper.

REFERENCES

[1] T.W. Ellis, L. Levine, R. Wicen, "Copper: Emerging Material for Wire Bond Assembly", Solid State Technology, Vol. 43, No. 4, pp. 71-71, 2000.
[2] T.B. Massalski, H.W. King, "Alloy Phases of the Noble Metal", Progress in Materials Science, Vol. 10, pp. 3-78, 1963.
[3] Z.H. Zhao, F.C. Qi, S. Zhao, M. Lei, "Research on Fatigue Properties of Micron Scale Copper Bonding Wires", Key Engineering Materials, Trans Tech Publications Ltd, Vol. 734, pp. 176-184, 2017.
[4] L. Pierre, "Diagnosis Underground Cables by Detecting Partial Discharges", Graduation Study, Faculty of Applied Sciences University of Liege, Belgium, 2010.
[5] D. Francois, "Damage and Rupture of Materials", Sciences, 2004.
[6] G. Richard, A.R. Salama, K. Medles, C. Lubat, S. Touhami, L. Dascalescu, "Electrostatic Separation of Two Types of Copper Wires from Electric Cable Wastes", Proceedings of the Electrostatics Joint Conference, West Lafayette, pp. 13-16, USA, 2016.
[7] G. Richard, A.R. Salama, K. Medles, C. Lubat, S. Touhami, L. Dascalescu, "Experimental and Numerical Study of the Electrostatic Separation of Two Types of Copper Wires from Electric Cable Wastes", IEEE Transactions on Industry Applications, Vol. 53, No. 4, pp. 3960-3969, 2017.
[8] B. Smyrak, M. Gnielczyk, B. Jurkiewicz, T. Knych, K. Korzen, M. Jablonski, A. Mamala, A. Nowak, "Research of Chemical Composition Influence on the Mechanical and Electrical Properties of Al-Mg-Si Wires", Key Engineering Materials, Vol. 682, pp. 138-142, 2016.
[9] B.S. Bernstein, E.L. Brancato, "Aging of Equipment in the Electric Utilities", IEEE Transactions on Electrical Insulation, Vol. 28, No. 5, pp. 866-875, 1993.
[10] H. Henao, G.A. Capolino, M. Fernandez Cabanas, F. Filippetti, C. Bruzzese, E. Strangas, R. Pusca, J. Estima, M. Riera Guasp, S. Hedayati-Kia, "Trends in Fault Diagnosis for Electrical Machines: A Review of Diagnostic Techniques", IEEE Industrial Electronics Magazine, Vol. 8, No. 2, pp. 31-42, 2014.
[11] R. Sarathi, D. Supriyo, C. Venkataseshaiah, N. Yoshimura, "Investigations of Growth of Electrical Trees in XLPE Cable Insulation under Different Voltage Profiles", Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 666-669, 2003.
[12] H. Ouaomar, N. Mouhib, M. Lahlou, M. El Ghorba, "Mechanical Behavior and Specific Energy in Elastic Phase of Aluminum Wires and Copper Wires Belonging to Low Voltage Underground Electrical Cable", The International Journal of Engineering and Science (IJES), Issue 4, Vol. 8, pp. 27-32, 2019.
[13] A. Ouafik, A. Wahid, M. Idiri, A. Abouzaid, B. Boubeker, "Mechanical Characterization and Statistical Study of Copper Electrical Wires in an Overhead Line" International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 51, Vol. 14, No. 2, pp. 261-266, June 2022.
[14] H. Chaiti, A. Moumen, M. Jammoukh, Kh. Mansouri, "Numerical Modeling of the Mechanical Characteristics of Polypropylelne Bio-Looaded by Three Natural Fibers with the Finite Element Method", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 49, Vol. 13, No. 4, pp. 45-50, December 2021.
[15] A. Lakhdar, A. Moumen, K. Mansouri, "Study of the Mechanical Behavior of Bio Loaded Flexible PVC by Coconut and Horn Fibers Subjected to Aging", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 46, Vol. 13, No. 1, pp. 75-80, March 2021.
[16] H. Ouaomar, N. Mouhib, M. Lahlou, M. El Ghorba, "Mechanical Behavior and Statistical Study of Aluminum wires Belonging to Low Voltage Underground Electrical Cable", International Journal of Innovation and Scientific Research, Vol. 4, No. 3, pp. 06-10, 2015.
[17] N. Mouhib, H. Ouaomar, M. Lehlou, M. Barakat, M. El Ghorba, "Application of Student and Weibull Statistical Distributions on Experimental Tensile Test Results of Steel Wires Extracted from Anti Gyratory Wire Rope (17*9)", International Journal of Advanced Research in Science and Technology, Vol. 6, pp. 498-501, 2015.
[18] A. Wahid, N. Mouhib, A. Ouardi, A. Kartouni, H. Chakir, M. El Ghorba, "Wire Rope Reliability Assessment based on Damage Mechanics", Int. Jour. of Performability Engineering, Vol. 15, No. 6, pp. 1744-1750, 2019.

[19] H. Ouaomar, N. Mouhib, B. Saadouki, M. Lahlou, M. ELghorba, "Mechanical Behavior and Statistical Study of Copper Wires Belonging to Low Voltage Underground Electrical Cable", Int. Journal of Innovation and Scientific Research, Vol. 19, No. 2, pp. 252-258, December 2015.

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