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CORRELATION BETWEEN ELECTRICAL CONDUCTIVITY AND STRAIN HARDENING EXPONENT OF AL-CU-FE-ZR ALLOY SUBMITTED TO HEAT TREATMENT (150 ° / 2H)

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Abstract. The aim of this work is to analyze the influence of the heat treatment on the electrical conductivity and Strain Hardening Exponent [η] of Al-0,05% Cu-0,40% Fe-0,22% Zr alloy, whose ingots were obtained by die casting in "U" shape, machined and separated into two batches: the first is the material without heat treatment; the second was heat treated for two hours at 150 ° C. Subsequently, samples from both batches were cold rolled in diameters [4.0; 3.8; 3.0; 2.7] mm. The obtained wires were submitted to the electrical resistivity test and to the tensile test, in which the Electrical Conductivity and Strain Hardening Exponent [η] were determined through the tensile test data applied to the Hollomon method. It was observed that the wires with diameter 3.0 mm showed the highest values of Electrical Conductivity.

Keywords: Al-Zr Alloy, Heat treatment, Thermorresistivity, Strain Hardening

1. INTRODUCTION

Energy consumption is one of the main indicators of economic development and the quality of life of any society. It reflects both the pace of activity in the industrial, commercial, and service sectors, as well as the population's ability to acquire technologically more advanced goods and services, such as automobiles (requiring fuels), appliances and electronics (which require access to the power grid and press the consumption of electric energy) (ANEEL, 2017). Due to the excessive growth of this consumption and socioeconomic development, there is a great complexity in meeting this demand, which can lead the country to an energy crisis (Ambrosi and Gonzatto, 1993).

In Brazil, it is a challenge to transport electric energy between regions, especially distancing large hydroelectric projects from the North to large energy consumption centers, as well as the Luz para Todos Project, which aims to connect consumers far away in the North Region (Cardoso, 2017).

Aluminum presents excellent characteristics regarding electrical conductivity and mechanical strength. However, the Al-EC (electroconductor aluminum) currently used in electric energy transport systems, works at maximum working

temperature of 90 ° C without loss of mechanical properties (Regis, 1999). In this context, research is carried out on aluminum alloys and alloying elements in order to achieve the desired properties, which, for electric power transmission wires, are high mechanical strength and electrical conductivity.
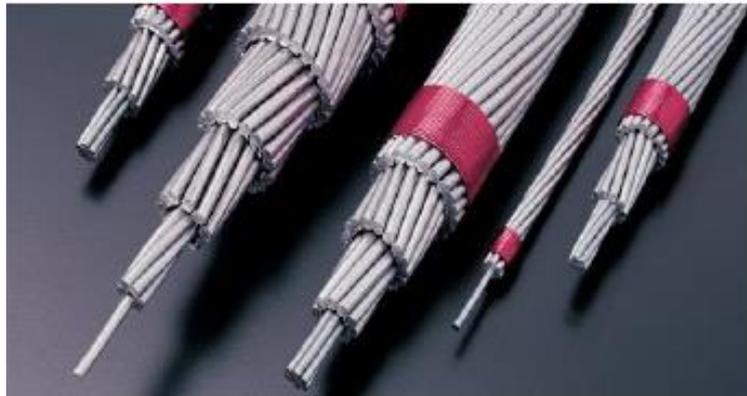

Figure 1 – Aluminium wires, used to transmit electrical energy. Source: ABAL, 2019

2. MATERIALS AND METHODS

The alloy was obtained by direct casting from the Al-EC alloy, called Electroconductor Aluminum. Copper, Iron and Zirconium elements were added in the percentages of 0.05%, 35-45% and 0.22% respectively. The alloy has been cast in a U-shaped metal cup, which provides sufficiently rapid cooling rates for retention of Zr in solution, such that the molten material is found to be a "melt temper".
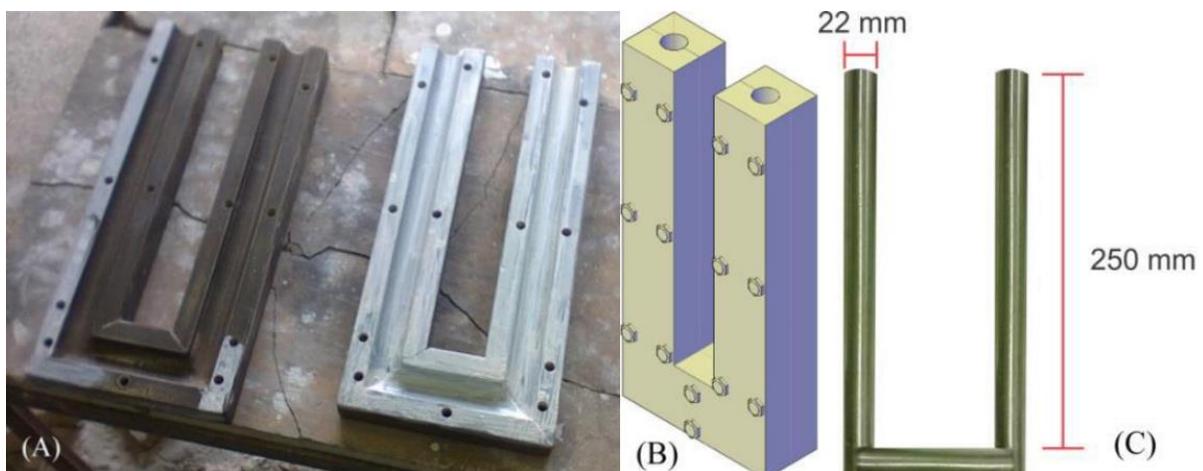

Figure 2- U-shaped ingot. (A) Open ingot; (B) Schematic drawing of the mold U; (C) Test piece with dimensions. Source: Cardoso, 2017.

The alloys were machined to a diameter of 18.0 mm and the profiles were separated into two batches: in the first, in the condition as the cold deformation was carried out; and the second was subjected to a heat treatment at 150 ° C for a period of two hours and then subjected to cold rolling to reach the diameters [4.0; 3.8; 3.0; 2.7] mm.
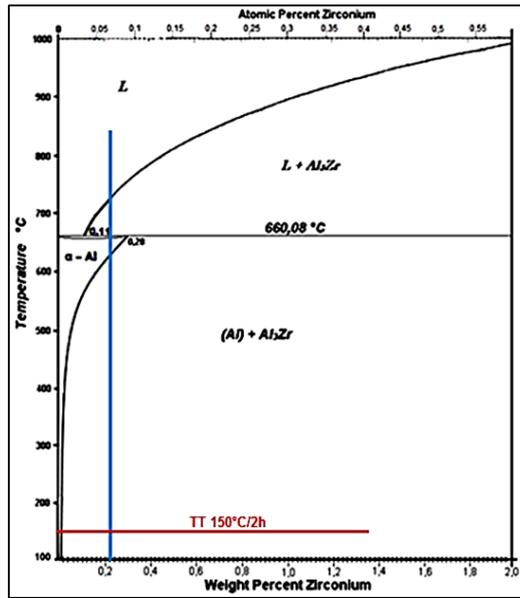
Figure 3- Al-Zr diagram showing composition used and applied heat treatment temperature. Source: Cardoso, 2017

One of the parameters used to evaluate the mechanical characteristics of the materials is the strain hardening exponent [η], obtained through the results of the tensile test, whose calculation is performed according to the Hollomon's equation (Nutor, 2017):

$$\sigma = K\varepsilon^{\eta} \tag{1}$$

Where σ is the true stress, ε is the true strain, η is the strain-hardening exponent and K is the strength coefficient. In the Hollomon's expression, the strain-hardening exponent measures the ability of a metal to strain-harden. Larger magnitudes indicate larger degrees of strain hardening (Nutor, 2017).

The Hollomon equation can be linearized using the logarithmization technique, according to Eq. 2.

$$log(\sigma) = log(K) + \eta log(\epsilon) \tag{2}$$

The strain hardening exponent [η] is the angular coefficient of the curve described by Eq. 3, such that:

$$\eta = \frac{\log \sigma - \log k}{\log \epsilon} \tag{3}$$

For the alloys without heat treatment [NHT] and with heat treatment [TT 150 ° C / 2h] the macrostructural characterization was carried out, Electrical conductivity tests following the norm NBR-6814 and Tensile tests to obtain the strain hardening exponent [η], for all diameters obtained.

Figure 4 – Microhmimeter and samples used for electrical characterization. Source: Cardoso, 2017

Separated samples were were grounded with abrasive silicon carbide abrasive sandpaper with decreasing particle size # 80, # 100, # 220, # 400, # 600, # 800, # 1000, and # 1200, and then etched by immersion in Keller reagent (2mL HF, 3mL HCl, 5mL HNO_3, 190mL H_2O). After the chemical attack, the samples were washed in running water and rinsed with alcohol to capture the images of the structures as molten, non-heat treated [NHT] and heat treated [TT 150 ° C / 2h]

3. RESULTS AND DISCUSSIONS
3.1 Chemical composition

After the melting of the alloy, the chemical composition was obtained using a Bruker ® optical emission spectrometer (Fig.5). The result of the chemical composition of the material produced, presented in Table 1, was obtained, indicating that all the procedures were carried out in an adequate way and the chemical composition obtained does not suffer great fluctuations, in agreement with the scope of this work.

Figure 5 - Q4 TASMAN Optical emission Spectometer. Source: Prazeres, 2014

Table 1: Chemical composition of the base alloy, after solidification.

Al-0,05Cu-[0,35-0,45]Fe-0,22Zr Alloy	Elements [%p]		
	Cu	Fe	Zr
	0,051	0,397	0,218

Source: From the survey.

3.2 Macrostructural characterization

Figure 6 shows the macrostructures of Al-0.05% Cu- [0.35-0.45]% Fe-0.22% Zr alloy, revealed by etching with 0.5% Keller solution. For the analysis of the macrostructure, one must consider the two conditions under which the samples were obtained.
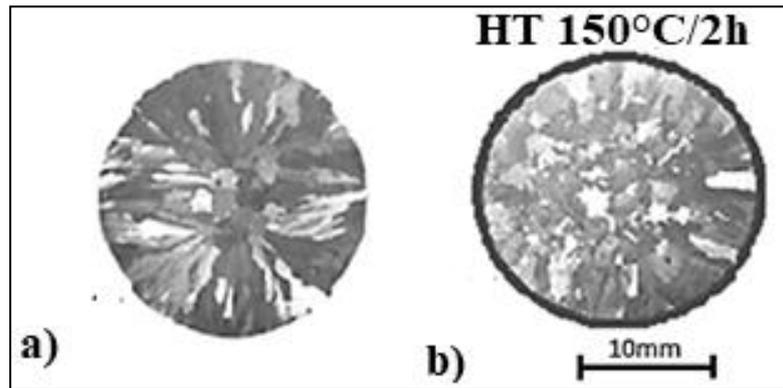
Figure 6- Macrostructure of Al-0.05% Cu-0.40% Fe-0.22% Zr alloy: [A] as the saturated solid solution of Zr in Al; [B] as heat treated at 150 ° C / 2h. Source: Cardoso, 2017.

The analysis of the images of the macrostructure allows to make the following observations:
i.   The crude fusion macrostructure shows that the alloy in the [NHT] condition is predominantly formed by columnar grains.
ii. The alloy in the condition [TT 150 ° C / 2h] did not present effective refining. However, the structural arrangement was modified, resulting in more fragmented grains, which apparently presented greater equiaxiality. Therefore, to better understand the phenomena involved in the heat treatment, it is necessary to evaluate the variations of the characteristics of the material and its relations with the strain hardening exponent.

3.3 Mechanical conformation

The cold forming process changes the characteristics of the material. Thus, as the material is laminated, some of the applied stresses are transmitted to the crystalline structure and modify the network parameters. Figure 7 indicates the intensity of cold work and the degree of deformation accumulated during rolling. It is observed that the wire of diameter 2.7 mm presents a higher percentage of cold work suffered. However, the wire diameter 3.0 mm has the largest accumulation of deformation among the four diameters studied.
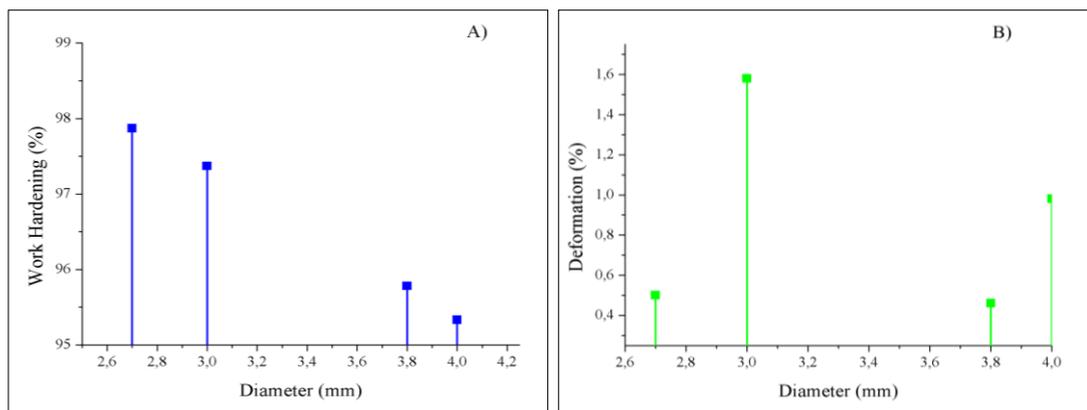

Figure 7- (a) Total cold work achieved during rolling and (b) degree of deformation for each laminate chain of the specimens. Source: From the survey

3.4 Correlation between Electrical Conductivity and Strain Hardenig Exponent

Figure 8 illustrates the comparison between the Electrical Conductivity and [η] results for the STT alloy and post-heat treatment, together with the scheme of variation of the properties of the deformed materials during the hardening and recovery stage.
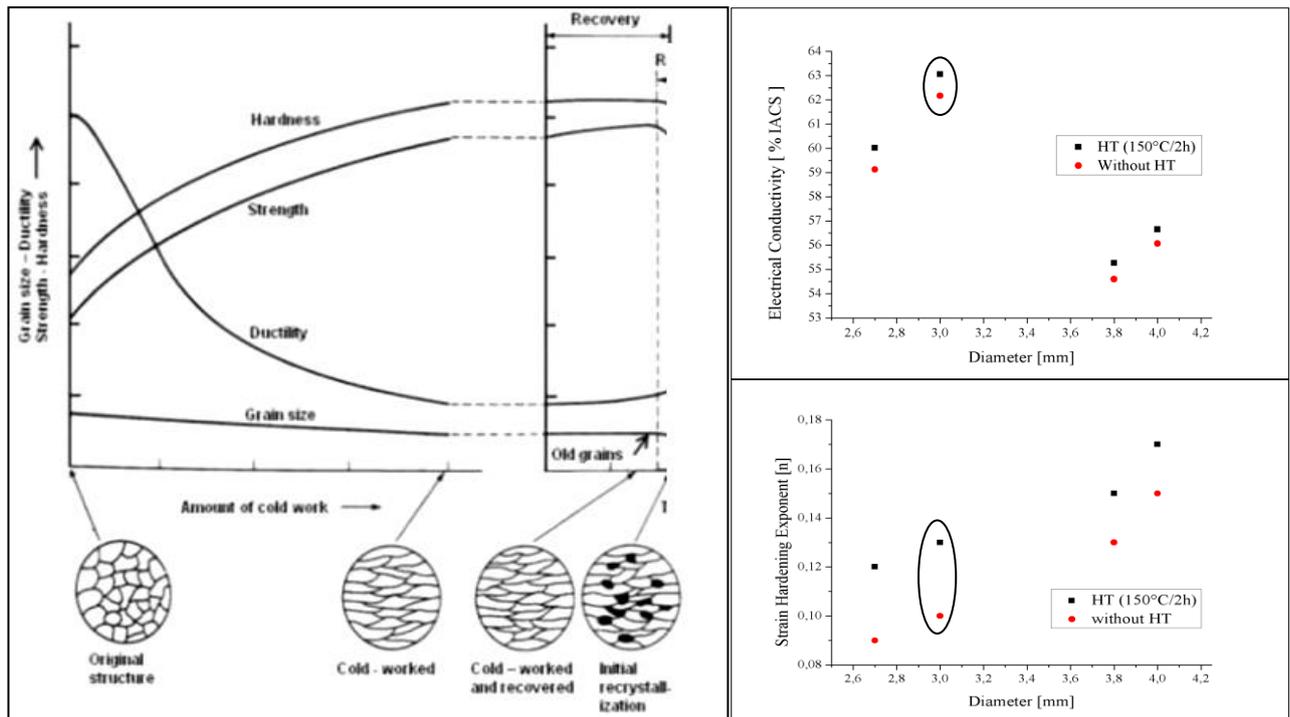
Figure 8- (a) Electrical Conductivity; (b) strain hardening exponent [η] for Al-0.05% Cu-0.35% Fe-0.22% Zr alloy in the conditions [NHT] and [TT 150 ° C / 2h], compared to the scheme of variation of properties with dynamic recovery. Source: Adapted from Cardoso, 2017.

4. CONCLUSIONS

The correlation between the values obtained for Electrical Conductivity and for [η] allows the following comments:

i.   The wire diameter 3.0 mm was highlighted because it presented the highest values of Electrical Conductivity. As this wire is the one that accumulates a greater degree of cold deformation, it is probable that it presents a more favorable condition for the dynamic recovery to occur, raising Electric Conductivity.

ii.   The alloy in the condition [TT 150 ° C / 2h] presented superior electrical performance. Heat treatment, under low temperature conditions [150 ° C] and short time [2 h], by promoting the stress relief of the structure as "melt anneal", improves the yarn's dynamic recovery capacity, which may favoring gains in Electric Conductivity.

5. REFERENCES

ABAL – Associação Brasileira do Alumínio. Aplicações: Indústria Elétrica. Disponível em: http://www.abal.org.br/aluminio/historia-do-aluminio. Acesso em 28/02/2019.

ABNT - Associação Brasileira de Normas Técnicas – "Fios e cabos elétricos - Ensaio de resistência elétrica", Rio de Janeiro, Mar. 1986, NBR 6814.

ALBUQUERQUE, V. H. C. de; CORTEZ, P. C; ALEXANDRIA, A. R. de; AGUIAR, W. M; SILVA, E. de M. BUTTON, Sérgio. Conformação plástica dos metais (2007) Disponível em: http://www.fem.unicamp.br/sergio1/pos graduação/MR640/questresp.html Acesso em 06 mar. 2016.

AMBROSI, I; GONZATTO, V. Situação energética no Brasil e alternativas frente a falta de investimento no setor. Teor. Evid. Econ, Passo Fundo, ano 1, p. 143-164, 1993

AMERICAN SOCIETY FOR METALS - ASM INTERNATIONAL, Alloy phase diagrams, v. 3, ASM Handbook, 1992.

ASM INTERNATIONAL – American Society of Materials, Aluminum and Aluminum alloys. v. 4. American Society for Metals - ASM Handbook, 1998.

ASTM - American Society for Testing and Materials. B941-16: Standard Specification for Heat Resistant Aluminum-Zirconium Alloy Wire for Electrical Purposes. West Conshohocken, 2011.

Ambriz, R. R.; Jaramillo, D. Mechanical Behavior of Precipitation Hardened Aluminum Alloys Welds. Disponível em: http://dx.doi.org/10.5772/58418. Acesso em 05 fev. 2017.

ANEEL – Agência Nacional de Energia Elétrica. Anuário estatístico de Energia elétrica 2017. Disponível em: http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao160/topico-168/Anuario2017vf.pdf. Acesso em 20/02/2019

Askeland, D. R.; Phulé, P. P. Ciência e Engenharia dos Materiais. São Paulo: Cengage Learning, 2013

Barlat, F.; Duarte, J. F.; Rauch, E. F.; Gracio, J. J. Hardening Behavior and Structural Evolution upon Strain Reversal of Aluminum Alloys. Scripta Materialia 46(12): 881-886. Jun, 2002.

Boyer, H. E. Heat Treating of Nonferrous Alloys. Metallogr. Microstruct. Anal. (2013) 2:190–195 CHIAVERINI, V. Tratamento térmicos das ligas metálicas. São Paulo: ABM. 2008

Cardoso, M.F.M. Efeito do tratamento térmico sobre o coeficiente de encruamento para uma liga Al-Cu-Fe-Zr. Dissertação (Mestrado). Programa de pós-graduação em Engenharia Mecânica. Universidade Federal do Pará. Belém, 2017

Cavassin, R. S. Uma abordagem multicritérios para recapacitação de linhas de transmissão. Dissertação de Mestrado Universidade Federal do Paraná, Curitiba, 2011.

COMPANHIA PARANAENSE DE ENERGIA ELÉTRICA – COPEL – Especificação 00000-30009-082. Especificação técnica para cabos de alumínio termorresistente com alma de aço. Rev 01, PR, 2006, 26 p. COLPAERT, H., Metalografia dos Processos Siderúrgicos Comuns. 4°Ed., Blucher, 2008.

D´oliveira, A. S. C. M., Ph.D. Profa Titular/DEMEC - UFPR- TM 704 – Metalurgia Física PIPE e PG-MECdisponível em: Acesso em: 05 de Dezembro de 2016.

Dieter, G. E. Mechanical metallurgy. Ohio: McGraw-Hill Kogakusche, Ltd. International student edition. American society for metals-ASM, v.1, 1976, p. 214.

Eletro. Disponível em: < http://www.eletrobras.com/elb/data/Pages/LUMIS2 93E16C4PTBRIE.htm >. Acesso em 10 Jan 2017.

Nutor, R.K.; Adomako, N.K.; Fang, Y.Z. Using the Hollomon model to predict strain-hardening in metals. American Journal of Materials synthesis and processing. 2017. v 2(1), p. 1-4.

Prazeres, E.R. Estudo do tratamento térmico e da modificação da liga Al0,05%pCu-[0,24-0,28]%pFe-0,6%pMg com a adição de 0,03%pNi. Trabalho de Conclusão de Curso (TCC). Faculdade de Engenharia Mecânica. Universidade Federal do Pará. 2014.

6. RESPONSIBILITY NOTICE

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