



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

COB-2019-2048

INFLUENCE OF HARDENING IN THE MECHANICAL, ELECTRICAL AND STRUCTURAL PROPERTIES OF AL-0.05%CU-0.27%FE-0.6%MG-0.15%TI ALLOY

Beatriz Seabra Melo¹

Vinicius Silva dos Reis¹

e-mail: beatrizseabra@hotmail.com

e-mail: viniciusreis11@hotmail.com

Natália Luiza Abucater Brum¹

e-mail: naty_abucater@hotmail.com

Mauro Quaresma Lobato¹

e-mail: mauroqlobato@gmail.com

Emerson Rodrigues Prazeres¹

e-mail: engemersonrodrigues@outlook.com

José Maria do Vale Quaresma¹

e-mail: jmquaresma@ufpa.br

¹ UFPA – Federal University of Pará – GPEMAT GROUP – 01 Augusto Corrêa Street. Belém, PA 66075-110, Brazil

Abstract. *The increase in population, as well as the growing need to supply it, results in a constant increase in the demand for electricity, requiring the improvement of cables for its transmission and distribution. This work aims to analyze the influence of heat treatment on the base alloy Al-0.05% Cu-0.27% Fe-0.6% Mg-0.15% Ti. The alloy was obtained by casting in “U” mold, the molten material was machined and rolled to a diameter of 3.0 mm. After cold work, some specimens were preserved without heat treatment (WHT), others underwent aging heat treatment (HT) for 6 hours at 200°C and the last portion was subjected to the term resistivity test according to the Standard. ASTM B941. The structural, electrical and mechanical characterization of the alloy was performed through metallographic analysis, electrical conductivity test and tensile test, respectively. All these procedures were performed in order to analyze and compare the structural characteristics, electrical and mechanical behavior of the alloy before and after HT and to validate the material as a resistant term. It was found that artificial aging applied for 6 hours to the samples refined the grain of the structure and caused a slight increase in the electrical conductivity of the material, but with a decrease in TSL.*

Keywords: *Aluminium alloy, Rolling, Electrical conductivity, Aging, Mechanical characterization*

1. INTRODUCTION

The consumption of electric energy can be considered an indicator of socioeconomic development for any nation, according to the Ministry of Mines and Energy (2008). Since energy demand is of the utmost importance both in industrial, commercial and service growth, as well as in population capacity to acquire goods and services this is evidenced, Sorrell (2015). During the last decades, there has been an increase in demand for electric energy, demanded by industry and households. The satisfaction of this demand generates numerous problems, such as, manufacturing and constructing new cables for high voltage with new materials. And this fact does not only happen in highly populated urban areas, but in all national territory. The challenge generated attracts investments to build new lines to supply the demand centers, on the other, it is possible to increase the transmission capacity (Tx) and distribution (Dx) of electricity of the existing lines, using cables manufactured with new metal alloys.

Pure aluminum does not have satisfactory mechanical strength, however its alloys have good mechanical properties coupled with the high electrical conductivity and light weight of these cables. The properties of these alloys can be further improved with studies on the addition of various alloying elements and their effects on material structure, as

well as the application of heat treatments. According to Quaresma (1999), the structure of the material is of paramount importance, since it is correlated with the mechanical, physical and chemical properties of the material of the piece.

It is through aluminum wires and cables that utilities carry electricity throughout the country. Only aluminum combines good electrical conductivity and excellent mechanical strength with extreme lightness. Differentials that revert to higher power transmission capacity, resistance to high temperatures without loss of physical properties and much assembly economy, with specific weight significantly lower than other metals, the use of aluminum cables to carry electric current reduces the weight on the supporting structures, minimizing the cost of networks with lower investments and less maintenance (ABAL, 2019).

The objective of this work is to analyze the Al-0.05% Cu-0.27% Fe-0.6% Mg-0.15%Ti base alloy on the influence of the artificial aging thermal treatment at 200°C for 6 hours, and as well as the electrical and mechanical characterization before and after the treatment of thermoresistance of the solidified alloy in a metallic cast "U".

2. MATERIALS AND METHODS

The alloys were obtained by direct casting where an electrical aluminum conductor (Al-EC) was fused. The magnesium element was used in its pure form. A stoichiometric calculation was used to add 0.15%Ti. Subsequently all the elements were casted in the muffle furnace. Pouring was initiated with the removal of the test sample for chemical analysis. The solidification step of the alloys was through a U-shaped metal shell mold, seen in Figure 1. This mold was duly cured with alumina and sealed. Thus, obtaining the alloy pouring 0.05% Cu-0.27% Fe-0.6% Mg-0.15%Ti.

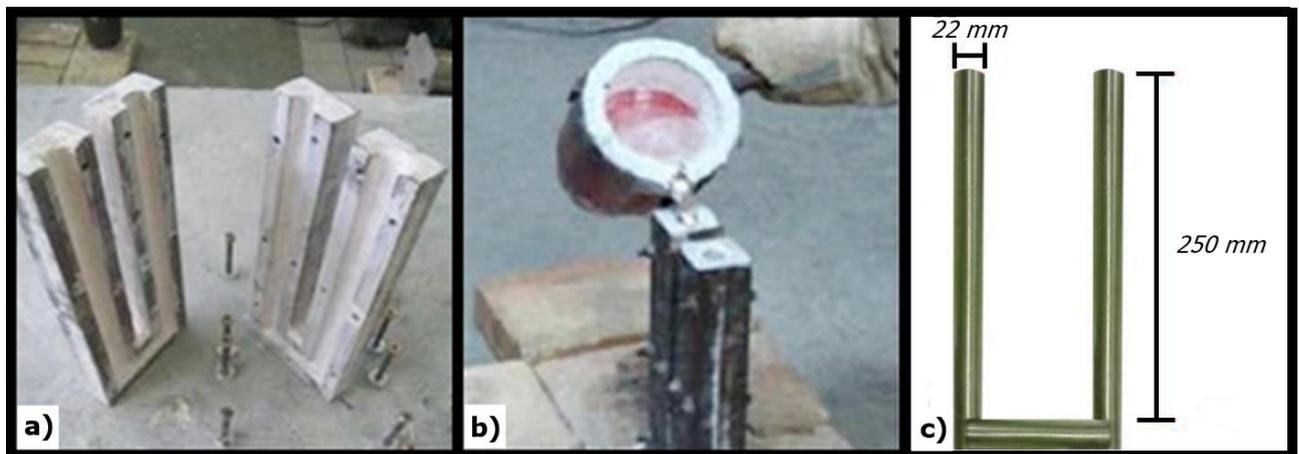


Figure 1. (a) Metallic chill in "U" format, (b) in moment pouring and (c) piece cast obtained. Available from: Archive GPemat.

After removal from the mold the material was sectioned and machined from 22 mm to 18.5 mm in diameter. Two samples were taken, one was preserved without heat treatment and the other was heat treated by means of artificial aging for 6 hours at a temperature of 200°C. The samples were sectioned in two parts, one for macrostructure analysis and the other undergoing cold work up to 3 mm in diameter. For the treatment the stove was used, in order to demonstrate the effect of the same in the alloy Al-0.05% Cu-0.27% Fe-0.6% Mg-0.15%Ti.

After the lamination, a portion of the samples obtained was used to perform the heat-resistivity test using the tensile machine. The thermoresistance test was performed according to ASTM B941, which describes that electrical conductors characterized as heat-resistant, should not show loss of more than 10% of their tensile strength limit when subjected to a temperature of 280 °C for one hour.

The alloy macrostructures were developed according to standard techniques in metallography following the sanding and buffing. The chemical attack was performed by immersion with Keller chemical reagent (2mL HF, 3mL HCl, 5mL HNO₃, 190mL H₂O) for macrostructure. The chemical composition of the alloys was obtained through an optical emission spectrometer model Q4 TASMEN.

The electrical and mechanical tests were performed on the 3 mm diameter wires, the samples were divided into 4 groups: without heat treatment, without heat treatment plus thermoresistance test, with heat treatment and with heat treatment plus thermoresistance test, this study culminated in four results for analysis. In the electrical characterization, the test bodies were submitted to the test with the objective of evaluating the electrical resistivity with the help of a multi-ohmmeter from the manufacturer MEGABRÁS. The electrical resistivity tests were carried out according to the norms NBR 6810 and NBR 6815. After the electrical characterization, the specimens were submitted to the mechanical test in a KRATOS tensile test machine, model IKCL1 - USB. The tensile tests were performed according to the norms for electric cables, NBR 6810, and metallic materials, NBR 6892, running them in three samples with 20 cm in length and 3 mm in diameter for each branch of the research.

3. RESULTS E DISCUSSIONS

3.1 Chemical analysis

Table 1 shows the chemical composition of Al-Cu-Fe-Mg-Ti alloy. This composition was previously obtained through stoichiometric calculations and validated from the optical emission spectrometer analysis and confirmed that the alloy is within the desired values for the purpose of the work.

Table 1. Chemical composition of fabricated aluminum alloy.

Alloy	Elements (% in mass)			
	Cu	Fe	Mg	Ti
Proposed composition of the alloy Al-Cu-Fe-Mg-Ti	0.05	0.2	0.5	0.15
Proposed composition of the alloy Al-Cu-Fe-Mg-Ti	0.054	0.274	0.583	0.148

The determination of the alloying elements and their respective concentrations have an influence on the properties obtained by the molten alloys. According to Sena (2015) iron contents in the range of [0.24- 0.28]% and 0.05% Cu are the most indicated to raise the tensile strength limit of the electrically conductive aluminum (Al – EC). The presence of magnesium significantly reduces the density of the alloy and reduces the stacking failure energy in aluminum, which causes a dynamic recovery temperature increase, allowing the alloy to retain cold working properties at higher temperatures prior to recovery. recrystallization occur (KAUFMAN; ROOY, 2004). According to Jorge (2013) titanium contributes to the elevation of the mechanical properties of aluminum alloys through grain refining.

3.2 Alloy macrostructure without deformation

Figure 2 shows the grain structure morphology of Al-0.05% Cu-0.27% Fe-0.6% Mg-0.15% Ti alloy without deformation, without heat treatment, in Figure 2.a, and after artificial aging for 6 hours in Figure 2.b, and the Al-Ti phase diagram is shown in Figure 2.c.

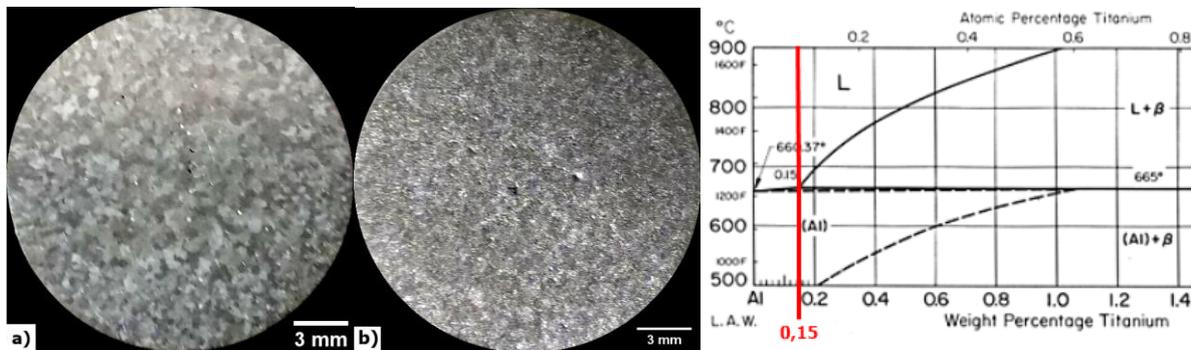


Figure 2. Alloy macrostructure (a) without heat treatment, (b) after heat treatment for 6 hours and (c) Al-Ti phase diagrams. Available from: Personal collection, 2019 and Infomet,2019.

The presence of predominant equiaxed grains is observed in both samples, however, for the sample to which artificial aging was applied for 6 hours, a reduction in grain size is visible, it is possible that the submission to treatment caused better dissolution of the grains. Aluminum matrix alloy elements.

Figure 2.c shows the Al-Ti phase diagram with the percent titanium (Ti) by weight used for the manufacture of the red-marked alloy, characterizing the alloy as diluted; as incapable of undergoing a peritetic transformation.

3.3 Electrical and mechanical characterization of the alloy

Table 2 presents the results of the electrical conductivity and tensile strength limit (TSL) tests on 3 mm diameter wires for Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti alloy in samples without heat treatment and heat treatment of 6 hours.

Table 2. Electrical conductivity tests and tensile strength limit values.

Heat Treatment	Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti	
	ELECTRICAL CONDUCTIVITY (%IACS)	TENSILE STRENGTH LIMIT (MPa)
WHT ⁽¹⁾	40.95	279.56
HT6h ⁽²⁾	41.59	272.48

(1) Without Heat Treatment
(2) Heat Treatment for 6 hours

Based on Table 2, electrical conductivity and TSL plots were prepared for the untreated (WHT) and 6-hour artificial heat treatment (HT + 6h) samples shown in Figure 3.a and 3.c, respectively. Figure 3.b shows the actual stress x strain curve obtained from tensile test data.

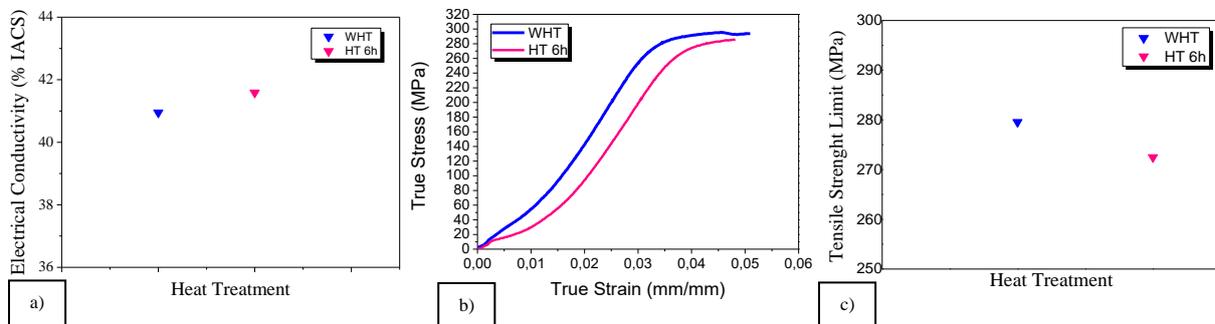


Figure 3. (a) Electric conductivity and (b) stress x strain true and (c) tensile strength limit (TSL) in relation to the treatment performed in the WHT and HT6h samples. Available from: Own authorship.

The difference in electrical conductivity and TSL values between WHT and HT6h samples is only 0.64% IACS and 7.08 MPa, respectively. This proximity between values is related to the application of cold plastic deformation to the material after heat treatment, before cold rolling the samples without heat treatment and heat treated had slightly different grains, however, the lamination causes crushing the grains, leaving the samples looking very similar.

Table 3 presents the results of the electrical conductivity and tensile strength limit (TSL) tests on 3 mm diameter wires for Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti alloy in samples without heat treatment and without heat treatment after the heat resistance test.

Table 3. Electrical conductivity tests and tensile strength limit values.

Heat Treatment	Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti	
	ELECTRICAL CONDUCTIVITY (%IACS)	TENSILE STRENGTH LIMIT (MPa)
WHT ⁽¹⁾	40.95	279.56
WHT + TR ⁽²⁾	52.49	177.72

(1) Without Heat Treatment
(2) Without Heat Treatment + Thermoresistance

According to Table 3, electrical conductivity and TSL graphs were prepared for the untreated (WHT) and untreated after heat resistance (WHT + TR) samples shown in Fi. 4.a and 4.c, respectively, Fig. 4.b shows the true stress x true strain curve obtained from tensile test data.

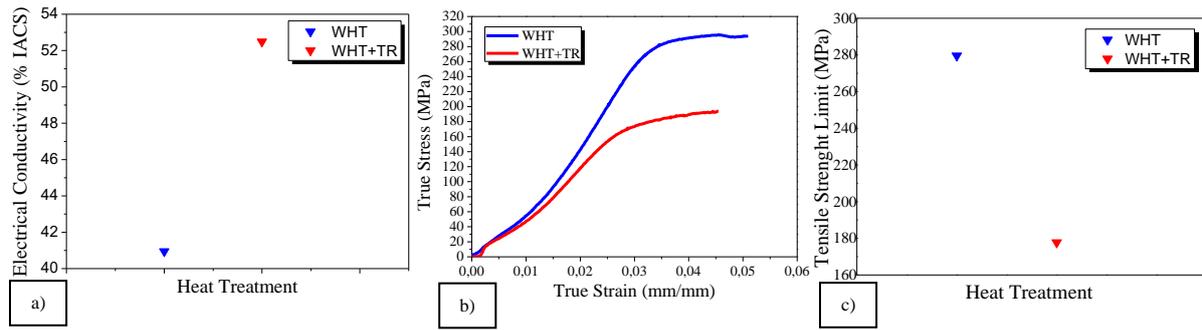


Figure 4. (a) Electric conductivity and (b) stress x strain true and (c) tensile strenght limit (TSL) in relation to the treatment performed in the WHT and WHT+TR samples. Available from: Own authorship.

Based on Figure 4 the sample with the best electrical performance is WHT + TR and the highest TSL is seen in the WHT sample. Both samples were subjected to the same degree of cold deformation, ie, hardened due to disagreement concentration, however the WHT + TR sample underwent heat treatment necessary for the heat resistance test, such treatment may have caused disagreement rearrangement resulting in decreased material hardening degree and consequently TSL, in addition the lower concentration of disagreements is favorable to free electron movement, thus explaining the increase in conductivity seen in the graph of Figure 4.a.

With the decrease in the hardening level the material deformation was expected to increase, however this did not happen, the true stress x true strain curve shown in Figure 4.c shows that although the stress relief applied caused a sharp drop in the TSL, a expected behavior did not cause the expected deformation effect. Thus it can be inferred that heat treatment based on ASTM B941 caused some vulnerability in the mechanical properties of the material.

Table 4 presents the results of the electrical conductivity and tensile strength limit (TSL) tests on 3 mm diameter wires for Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti alloy in samples with heat treatment for 6 hours and heat treatment for 6 hours after heat resistance test.

Table 4. Electrical conductivity tests and tensile strength limit values.

Heat Treatment	Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti	
	ELECTRICAL CONDUCTIVITY (%IACS)	TENSILE STRENGHT LIMIT (MPa)
HT 6h ⁽¹⁾	41.59	272.48
HT6h + TR ⁽²⁾	52.96	200.41

- (1) Heat Treatment for 6 hours
- (2) Heat Treatment for 6 hours + Thermoresistance

Also based on Table 4 were graphs of electrical conductivity, in Fig. 5.a, and TSL, in Fig. 5.c, to compare samples with heat treatment (HT6h) and with heat treatment after the test of heat resistance (HT6h + TR). Figure 5.b shows the true stress x true strain curve obtained from tensile test data.

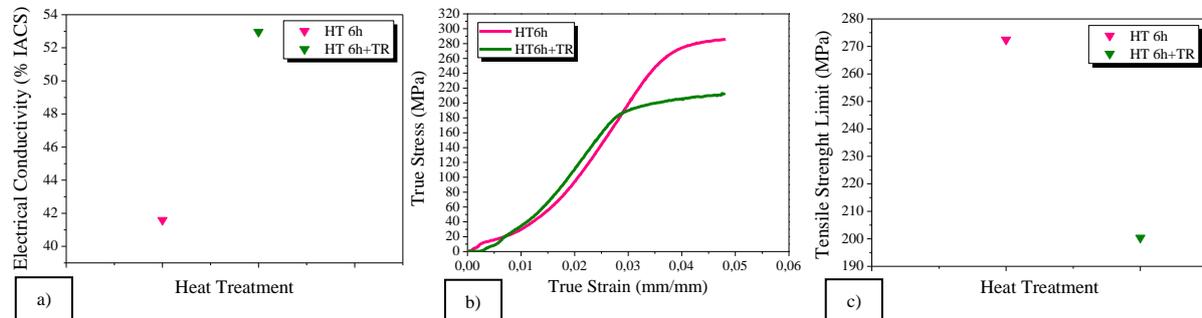


Figure 5. (a) Electric conductivity and (b) stress x strain true and (c) tensile strenght limit (TSL) in relation to the treatment performed in the HT6h and HT6h+TR samples. Available from: Own authorship.

Figure 5 shows that the sample with heat treatment for 6 hours (HT6h), with higher degree of hardening, has the highest TSL value and the lowest electrical conductivity when compared to the sample with heat treatment 6 hours after application of the test. heat resistance test (HT6h + TR). The heat treatment required to apply the ASTM B941 heat

resistance test may have decreased the degree of hardening and relieved internal stresses by rearranging the mismatches. In addition, Figure 5.b shows the actual stress x strain curves of the HT6h and HT6h + TR samples with marked change in TSL value and similar in deformation, thus verifying that the application of the heat resistance test caused the fragility of the material.

Correlating Figures 3, 4 and 5 shows that the electrical conductivity and TSL properties are inversely proportional to the studied alloy. This behavior may be related to cold deformation imposed on the alloy, according to Smith and Hashemi (2012), due to cold deformation, new disagreements arise and will interact with existing ones, as the density of disagreements increases with deformation, movement. They become increasingly difficult through the “forest of disagreements,” and then the hardening metal, that is, hardens by deformation due to increased disagreements. However, the concentration of disagreements causes greater resistance to the passage of free electrons, thus reducing the electrical conductivity.

The application of the treatment for the heat resistance test caused the great decay of mechanical properties, increase of electrical properties and kept the deformation of the material practically the same.

4. CONCLUSION

The study of structural characterization shows that the WTT sample, as well as the sample aged for 6 hours have very similar macrostructure with the presence of equiaxial grains thanks to the refining action of Titanium.

The sample with the best performance in electrical conductivity, besides the highest deformation, was artificially aged for 6 hours with the application of thermoresistance test (HT6h + TR) and the highest result obtained for mechanical property was the sample without heat treatment (WTT).

Based on the tests carried out in order to characterize the alloy, it can be concluded that the mechanical and electrical analysis after the thermoresistance test showed a subtle increase in the electrical conductivity and a decrease of more than 10% in the TSL for both the non-heat treated and artificially aged samples. Therefore, the Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti alloy cannot be classified as heat-resistant. However, although Al-0.05%Cu-0.27%Fe-0.6%Mg-0.15%Ti alloy does not present such satisfactory electrical properties, the mechanical performance obtained with respect to tensile strength presents good values.

5. REFERENCES

- ABAL, 2019. “Indústria Elétrica – Distribuindo energia através de fios e cabos”. 5 Jul. 2019 <<http://abal.org.br/aplicacoes/industria-eletrica/cabos-para-transmissao/>>.
- Associação Brasileira de Normas Técnicas (ABNT NBR 6815), 1981. *Fios e cabos elétricos – Ensaio de determinação da resistividade em componentes metálicos*. Rio de Janeiro, Brasil.
- Associação Brasileira de Normas Técnicas (ABNT NBR 6810), 1981. *Fios e cabos elétricos – Tração à ruptura em componentes metálicos*. Rio de Janeiro, Brasil.
- Associação Brasileira de Normas Técnicas (ABNT NBR 6892), 2002. *Materiais metálicos – Ensaio de tração à temperatura ambiente*. Rio de Janeiro, Brasil.
- American Society For Testing And Materials (ASTM B941), 2010. Standard Specification for Heat Resistant Aluminum-Zirconium Alloy Wire for Electrical Purposes.
- Brasil, M. M. E./E. P. E., 2008. “Projeções da demanda de energia elétrica para o plano decenal de expansão de energia 2008-2017”. 15 Jan. 2019 <[http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-245/topico-271/20080506_1\[1\].pdf](http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-245/topico-271/20080506_1[1].pdf)>.
- Jorge, I.C.S., 2013. *Estudo da coalescência de microcavidades na liga Al-0,05% Cu-[0,24-0,28]% Fe-0,7% Si modificada com os teores [0,05 e 0,15]% Ti para fins de transmissão [Tx] e distribuição [Dx] de energia elétrica*. Master Thesis in Mechanical Engineering, Universidade Federal do Pará, Belém, Brasil.
- Kaufman, J. G., Rooy, E. L., 2004. *Aluminum alloy castings: properties, processes and applications*. ASM International, USA, 1° ed.
- Knipling, E. K., Dunand, C. D., Seidman, D. N., 2008. “Precipitation evolution in Al-Zr and Al-Zr-Ti alloys during isothermal aging at 375-425 °C”. *Acta Materialia*. Vol. 56, No. 1. pp 114-127.
- Machado, P. C., 2012. *Análise da influência dos solutos de Zr e Ti sobre as propriedades mecânica, elétrica e de termorresistência de uma liga Al-Cu-Fe-Si destinada a Tx e a Dx de energia elétrica*. Master Thesis in Mechanical Engineering, Universidade Federal do Pará, Belém, Brasil.
- Prazeres, E. R., 2016. *Avaliação da modificação da liga base Al - Cu - Fe - Mg por teores de Ni e Ti quanto à caracterização estrutural, elétrica e mecânica, a partir de ligas solidificadas em molde “U”*. Master Thesis in Mechanical Engineering, Universidade Federal do Pará, Belém, Brasil.

- Quaresma, J. M.V., 1999. *Correlação entre condições de solidificação, microestrutura e resistência mecânica*. Doctoral Thesis in Mechanical Engineering, UNICAMP – Universidade Estadual de Campinas, São Paulo, Brasil.
- Sena, H. C. O., 2015. *Avaliação do feito do ferro em ligas de alumínio destinadas a condução de energia elétrica*. Master Thesis in Mechanical Engineering, Universidade Federal do Pará, Belém, Brasil.
- Smith, W. F., Hashemi, J., 2012. *Fundamentos de Engenharia e Ciência dos Materiais*. AMGH, Porto Alegre, 5^o ed.
- Sorrell, S., 2015. “Reducing energy demand: A review of issues, challenges and approaches”. *Renewable and Sustainable Energy Reviews*, Vol. 47, pp. 74-82.

6. RESPONSIBILITY FOR THE INFORMATION

The authors are solely responsible for the information included in this work.