INFLUENCE OF COPPER CONTENT ON WORKABILITY OF COLD ROLLED Al-Mg-Cu ALLOYS

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Abstract. *The market of cables to transfer and distribution of electric energy has strongly been developed during the last years due to the elevated mechanical strength and the reduced weight of their products.*

The thermal resistant cables can be used in a continuous work at temperatures up to 150ºC. When such conditions prevail, there is no evidence of decreasing on ultimate tensile strength (UTS), elongation and hardness, which can provide an increasing on the capability of electric energy transmission. According to such possibilities of high profitability and social support, it was proposed a research on developing a thermal resistant aluminium alloy, based on the binary Al-0.6wt%Mg alloy. Modifications must be done with the addition of copper (Cu) in order to obtain high thermal and electrical levels of conductivity.

Tensile tests were carried out before and after thermo resistivity test so that mechanical properties of the material could be evaluated. Further, electric resistivity tests were performed in the electric wires samples.

The obtained results have shown, in some cases, that copper content variation can improve the thermal resistance of the Al-Mg-Cu alloy. Additional tests are required to follow the proposed standards for cables fabrication.

Keywords: *Workability, Al-Mg-Cu Alloys, Thermal resistant cables.*

1. INTRODUCTION

In a technological context, the material structure is recognized to influence on mechanical properties, particularly when considering the tensile strength and ductility. Chemical and electrical characteristics are also affected by microstructural elements, such as dendrite arm spacing, porosity formation, inclusions, microsegregation, second phase's precipitation, etc [Quaresma, 1999; Garcia, 2000; Baptista, 2002].

The workability is a complex technological concept, which is related to the level of deformation of a material considering not only specific plastic forming processes such as rolling, wire drawing, extrusion and hot or cold forging but also the absence of surface defects. However, in some processes the workability limit is determined by the local necking down instead of the crack formation. Improving workability means improving the forming capacity of a material [Gavgali, 1998].

The workability process of the metal is focused on plastic deformation and fracture analysis [Dieter, 1976].

During a specific plastic deformation process, the workability, which can be defined as the capability that the material has to be deformed without showing cracks, is very important. Therefore, it is necessary to understand how the material behaves during the plastic deformation to measure and to forecast its limit before the fracture occurs [Taha, 2002].

The cold working is different form the hot working. The difference is in the fact that the cold worked metal has its strength increased due to the strain hardening, which is caused by the interaction between the dislocations and other types of defects such as grain boundaries, which stop their movement through the lattice. The structural deformations, piling and solidification defects have been strongly studied together with mechanical deformations, fracture and workability [Zu, 1999].

The growing demand in the production of electric energy cables and the necessity of the optimization in their performance are the main causes that have motivated the development of a new alloy with better characteristics. In this study, it was proposed an aluminium alloy that is thermo resistant with properties equivalent to those of the Al 1350 and 6101 alloy. Such alloy is able to keep good mechanical and electrical characteristics even in a high temperature conditions.

2. EXPERIMENTAL PROCEDURE

The chemical analysis of the aluminium alloys with 2.2wt%, 1,8wt%, 1wt%, 0,6wt% and 0,3%wt of cooper (Cu) was carried out in ALUBAR company by using a mass spectrometer. The results were attained from three analysis. The results are summarized in table 01.

Table 1 – Chemical Compositions of alloys (%).

Al-2.2wt%Cu-0.6wt%Mg	Si 0.0563	Fe 0.2009	Cu 2.2588	Ca 0.0008	Mg 0.6615	Zn 0.0005	Ni 0.0097	V 0.0046	Al 96.77
Al-1.8wt%Cu-0.6wt%Mg	Si 0.0580	Fe 0.2139	Cu 1.7899	Ca 0.0022	Mg 0.6020	Zn 0.0005	Ni 0.0124	V 0.0036	Al 97.82
Al-1.0wt%Cu-0.6wt%Mg	Si 0.0561	Fe 0.1793	Cu 1.0516	Ca 0.0003	Mg 0.5854	Zn 0.0005	Ni 0.0086	V 0.0030	Al 98.09
Al-0.6wt%Cu-0.6wt%Mg	Si 0.0571	Fe 0.1676	Cu 0.6153	Ca 0.0006	Mg 0.5841	Zn 0.0010	Ni 0.0073	V 0.0042	Al 98.54
Al-0.3wt%Cu-0.6wt%Mg	Si 0.0675	Fe 0.2910	Cu 0.3118	Ca 0.0007	Mg 0.6254	Zn 0.0113	Ni 0.0070	V 0.0088	Al 98.64

The Si compounds were kept lower than the usual Si percentage in 6101 alloy and the soft variation in the Cu and Mg contents was regarded to have no influence on the results.

Firstly, the alloys were melted by using an electrical resistance furnace. The magnesium content was maintained at 0.6%wt, whiel copper contained was changed according to the following sequence 2.2; 1.8; 1,0; 0.6 and 0.3 %wt. The alloys were poured in a specific metallic mold, which has a cylindrical shape to produce cylindrical metallic bars. These castings were machined until that the diameter reached 11mm. After the machining, the bars were cold rolled by using an electrical rolling mill up to the diameter of 3.9mm in order to obey the international requirements for electric cables.

The produced wires were submitted to a special heat treatment, in which the samples were heated at 230ºC for 1 h. According to COPEL standards for thermal resistant alloys the mechanical properties variation must not be higher than 10%. The tensile tests were carried out in a KRATOS MD 2000 machine before and after the heat treatment to evaluate the influence of the heat treatment on the mechanical properties of the material (UTS and elongation) and on its thermal resistivity. The electrical resistivity tests were in accordance with NBR 5287/1985 standard.

The samples, which were examined in the scanning electron microscope (SEM), were cleaned in alcohol-acetone solution (PA) by using ultrasound equipment for 10 min. Both the micrograph and the macrograph analysis of the samples were characterized in an optical microscope. The SEM used in this study is the LEO 1450 VP with a backscattered electrons detector (EBSD).

3. RESULTS AND DISCUTIONS

3.1. Electrical Conductivity and Tensile Tests

The wires obtained from the cold rolling were 3.9mm in diameter. The resistivity tests were performed to evaluate the electrical conductivity of the Al-Mg-Cu alloy. The figure 1 shows the behavior of electrical conductivity as a function of Cu content.

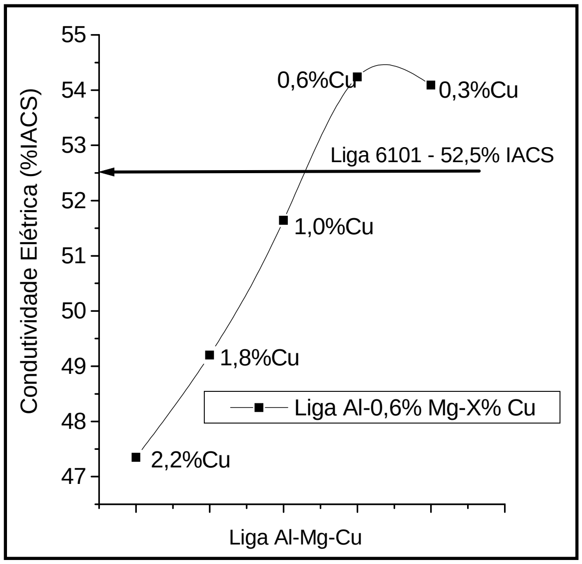

Figure 1 – Conductivity as a function of Cu content in Al-0,6wt%Mg-X%Cu

The figure 1 presents the evolution of the electrical conductivity as a function of the cooper (Cu) content in the alloys researched in this study. A tendency of increasing of conductivity can be seen while it was decreased the copper content. The red line in the graph indicates the level of electrical conductivity required for 6101 alloys [IACS - International Annealed Cooper Standard]. The alloy Al-1.0wt%Cu-0.6wt%Mg showed response similar to the 6101 commercial alloy. On other words, while IACS index is 52.5% for 6101 alloy, it was obtained about 51.5% IACS for the aforementioned alloy. Two other alloys (with 0.6wt% Cu and 0.3wt% Cu) showed excellent results, with 54.24 and 54.09% IACS, respectively. Those values are higher than that predicted in the NBR 5285/1985 standard for wires.

The evaluation of the mechanical behavior of the Al-Mg-Cu alloys as a function of the chemical composition and the heat treatment were made through tensile tests. The results obtained are shown in figure 2. The red lines show the standard values of the ultimate tensile strength (UTS) according to 1350 aluminum wires standard NBR 5118/1985) and 6101 alloy standard NBR 5285/1985.

The UTS results were included inside the range of minimum values required for the wire of 6101 alloy and for the wire of 1350 aluminum. Based on the results, it can be observed that the UTS increased with the (Cu) cooper content increasing and that all alloys presented a sensibility to the thermal action. In all the situations analyzed, the alloys have their strength (UTS) reduced.

The wire with 0.6%wt Cu presented a 5% decrease in UTS, and the wire with 0,3wt%Cu showed an almost constant UTS. Thus, both cases respected the limits previously established in COPEL standards.

In figure 2b, it is shown the evolution of the elongation before and after the heat treatment. It is possible to notice that the elongation reached values higher than the limit required, which is identified by the red arrow. It seems that ductility of the alloys was improved. These results suggest that a careful research about the phase precipitation kinetics and precipitation hardening has to be done.

Based on the results from tensile and electrical conductivity tests, the alloys Al-0.6wt%Mg-0.6wt%Cu e Al-0.6wt%Mg-0.3wt%Cu presented the best thermo resistant behavior. Hence, it seems that such alloys might be explored as commercial products. However, deep studies must be conducted. The alloy with 0.6wt% Cu is specially promising due to the highest electrical conductivity (54.24% IACS) founded and the satisfactory strength level of about 240 MPa, a little lower than that expected for commercial wires, considering diameters higher than 3.50mm.

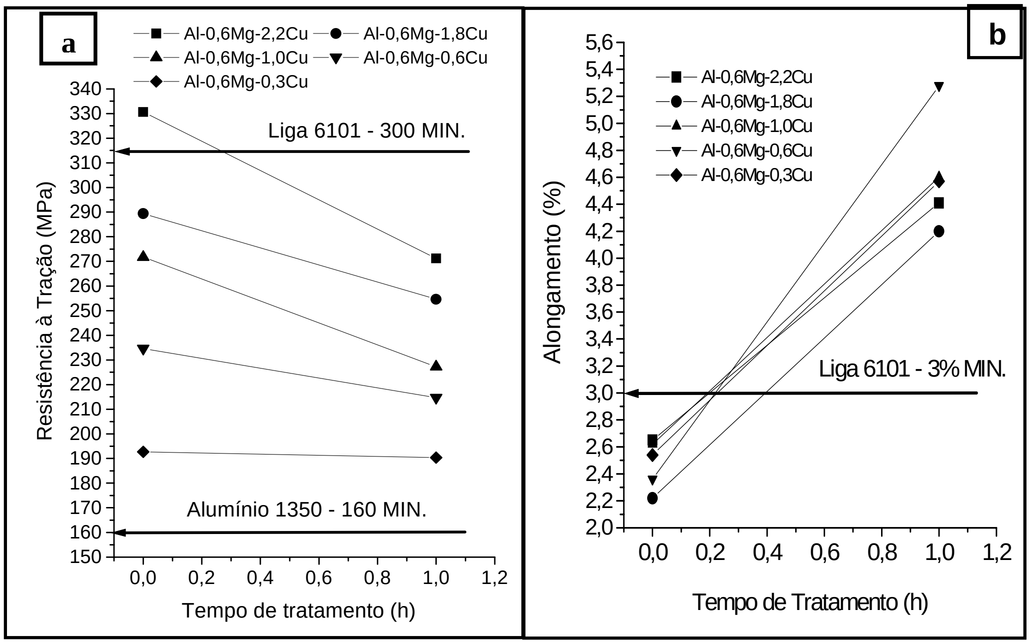

Figure 2 – Results obtained in tensile tests before and after heat treatment at 230°C for 1h (a) Ultimate tensile strength (UTS - MPa) and (b) elongation (%).

3.2. Fracture Analysis in SEM

3.2.1. Al-0.6wt%Mg-2.2wt%Cu alloy without heat treatment

The fracture surfaces morphology of the samples were examined in scanning electron microscope (SEM). The figure 3 shows the surface fracture corresponding to the alloy with 2.2wt%Cu before the heat treatment.

The figure 3a shows that the fracture surface presents smooth and plane morphology and no evidences of necking, which can indicate that the behavior of the fracture may be brittle. Fine dimples can be observed, probably due to the absence of precipitates. Further, microcavities can be noticed, indicating that the matrix was not affected by deformation. The probable cause of this behavior can be the presence of high levels of cooper (Cu) in the alloy (2.2wt%).

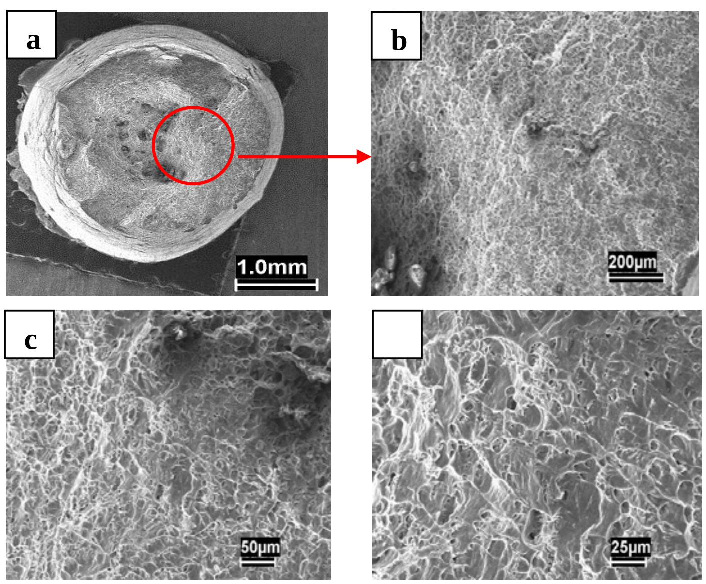

Figure 3 – SEM micrograph. (a) 25x Magnification; (b) Image from the region marked with the red circle in (a) – 100x; (c) 250x; (d) 500x.

In the Figure 4, it can be examined the curves corresponding to the chemical analysis in the fracture surface. The curve corresponding to cooper (Cu) has a similar shape to the curve of magnesium (Mg) and the curve of Fe shows a different behavior from the other elements, reaching 3wt% in the position 4 in Figure 4b.

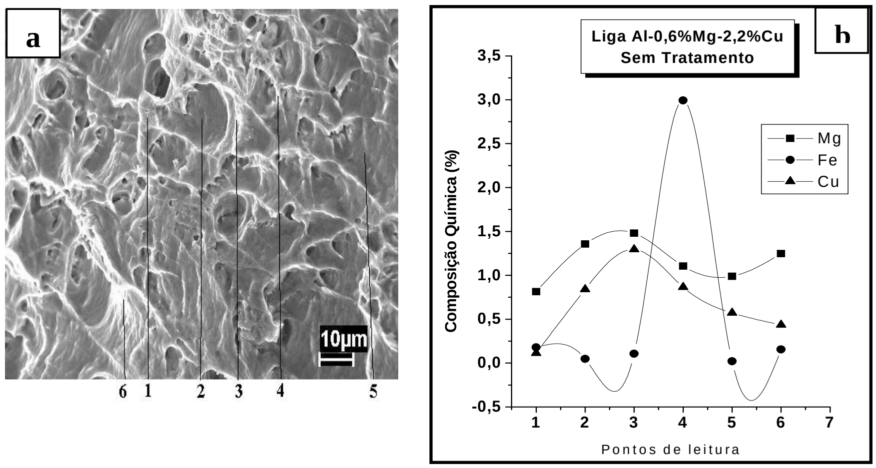

Figure 4 – Chemical composition analysis by SEM from fracture surface. (a) Micrograph of fracture and positions of chemical examining. (b) Segregation of elements Mg, Fe and Cu along fracture surface.

Al-0.6wt%Mg-2.2wt%Cu alloy with heat treatment at 230°C for 1h

The Figure 5 shows a fracture surface of Al-0.6wt%Mg-2.2wt%Cu alloy wire after heat treatment.

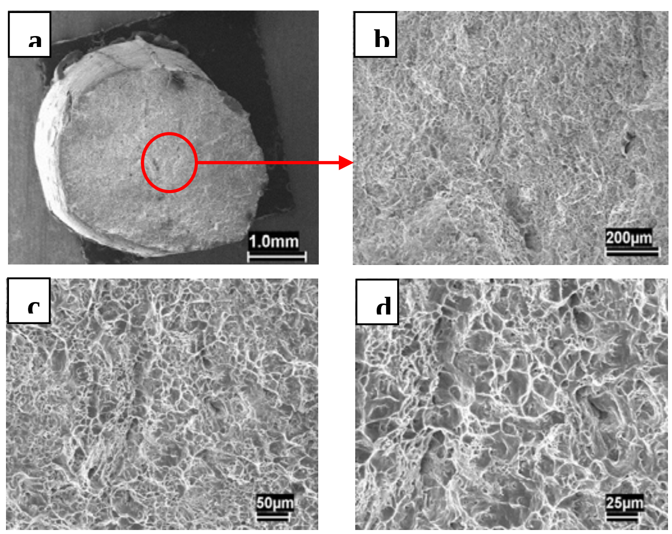

Figure 5 - SEM micrograph. (a) 25x Magnification; (b) Image from the region marked with the red circle in (a) – 100x; (c) 250x; (d) 500x.

In Figure 5 was noticed that cross section of fracture was not affected by significant deformation, which indicates brittle behavior. Besides, Figure 6d shows a dense net of thin dimples. Such characteristic seems to be related to temperature action during heat treatment, which intends to relieve reminiscent tensions from cold mechanical work of the wire.

The Figure 6 shows the chemical analysis of fracture surface for Al-0.6wt%Mg-2.2wt%Cu alloy after heat treatment.

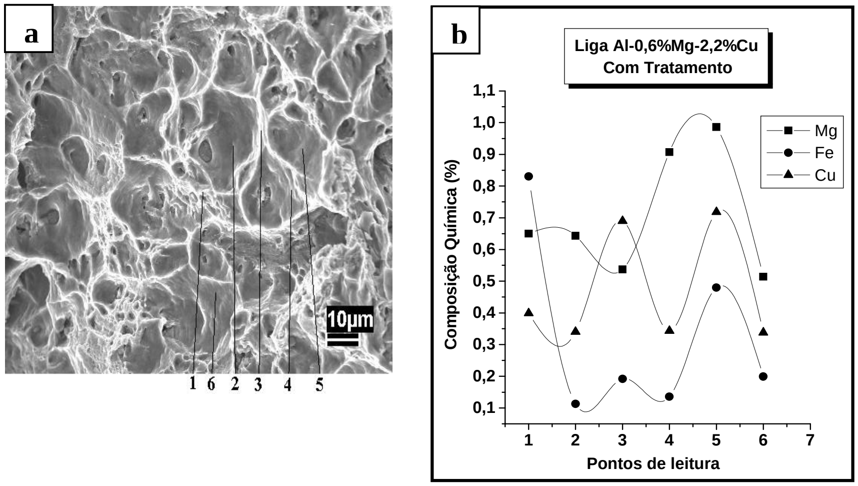

Figure 6 – Chemical composition analysis by SEM from fracture surface. (a) Micrograph of fracture and positions of chemical examining. (b) Segregation of elements Mg, Fe and Cu along fracture surface.

Figure 6b shows that copper and magnesium elements have the same tendency of segregation along fracture surface, while iron presents a distinct behavior. The iron seems to have much more mobility into aluminium matrix than the other elements.

Al-0.6wt%Mg-0.6wt%Cu alloy without heat treatment

The Figure 7 shows the fracture surface of Al-0,6%Mg-0,6%Cu alloy without heat treatment

Although low solute contents of this alloy, the fracture surface micrograph of Figure 7a shows the conical shape of the surface, which suggests a ductile behavior. The dimples in Figure 7d are thin and the microcavities appear without preferable orientation.

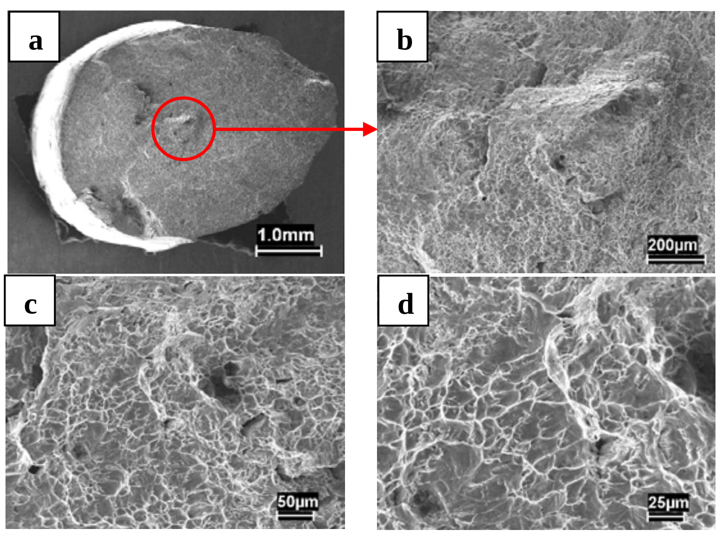

Figure 7 - SEM micrograph. (a) 25x Magnification; (b) Image from the region marked with the red circle in (a) – 100x; (c) 250x; (d) 500x.

Figure 8 shows the chemical composition analysis of fracture surface for Al-0,6wt%Mg-0,6wt%Cu alloy without heat treatment. It can be observed that copper and magnesium segregation tendencies are quite similar in the fracture surface. However, aluminum matrix seems to allow better mobility of iron compounds.

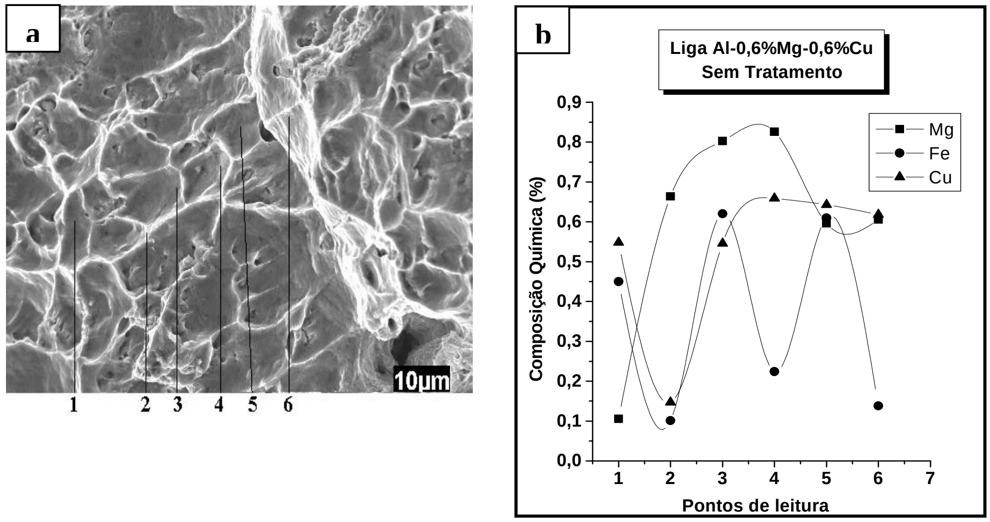

Figure 8 – Chemical composition analysis by SEM from fracture surface. (a) Micrograph of fracture and positions of chemical examining. (b) Segregation of elements Mg, Fe and Cu along fracture surface.

Al-0.6wt%Mg-0.6wt%Cu alloy with heat treatment at 230°C for 1h

Figure 9 shows the fracture surface of Al-0,6wt%Mg-0,6wt%Cu alloy after heat treatment.

Analyzing micrographs from Figure 9a, it was noticed that fracture surface is deep and conic. The necking down can also be observed. In Figure 9d, the dimples are dense and thin and the microcavities are non-oriented.

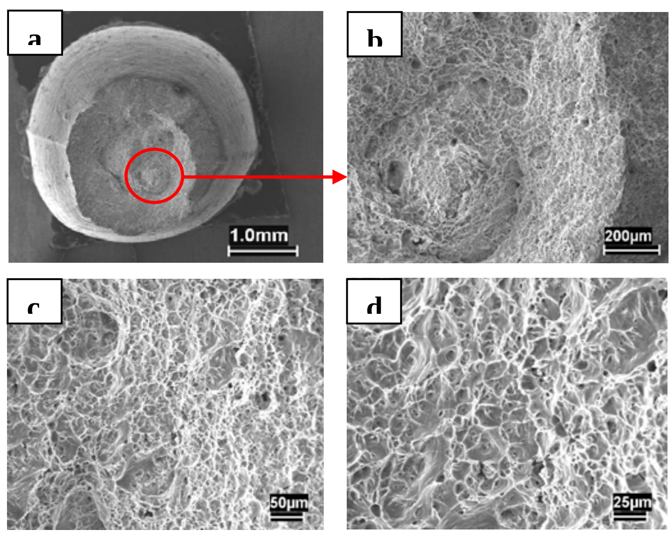

Figure 9 - SEM micrograph. (a) 25x Magnification; (b) Image from the region marked with the red circle in (a) – 100x; (c) 250x; (d) 500x.

Figure 10 shows the chemical composition analysis of fracture surface for Al-0.6wt%Mg-0.6wt%Cu alloy after heat treatment. It is evident that copper behavior was different to those mentioned before. No segregation along fracture surface can be considered to magnesium, since an almost constant behavior was observed. The iron shows a particular tendency when compared with the other elements at this specific situation.

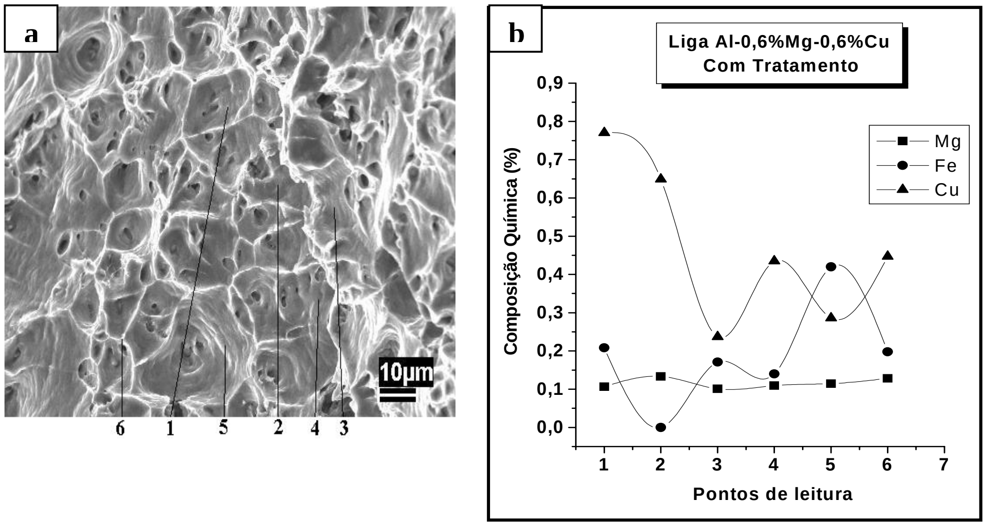

Figure 10 – Chemical composition analysis by SEM from fracture surface. (a) Micrograph of fracture and positions of chemical examining. (b) Segregation of elements Mg, Fe and Cu along fracture surface.

CONCLUSIONS

The studied alloy Al-Mg-Cu has a good workability due to all Cu contents examined were deformed plastically without suffering none alteration in its structures. Despite, it always presents fragile aspect in the fracture, except for the alloys with 0.6wt% and 0.3wt% of Cu. In the electric cables production, the wire ductility is an extremely important aspect, because it needs this property to be pos-manufactured.

The tensile test results and electrical conductivity measurements indicated that Al-0.6wt%Mg-0.6wt%Cu and Al-0.6wt%Mg-0.3wt%Cu alloys might be commercially explored but additional experiments should be performed. Such alloys showed good results concerning thermal resistivity response. However, the alloy with 0.6%wtCu seems to be the most promising since it presented higher electrical conductivity performance (54.24% IACS). Although the UTS value for this alloy was lower than expected (about 240 MPa), it can be considered a favorable result when it is compared with the minimum value required for the wire of 1350 aluminum (160 MPa). On the other hand, the thermal resistant behavior was excellent. Therefore, these results suggest that a careful research about the phase precipitation kinetics and precipitation hardening should be done.

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