INFLUENCE OF TITANIUM ON THE ELECTRICAL AND MECHANICAL BEHAVIOR OF AL-CU-FE-SI ALLOYS

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Abstract. *Due the growing demand for electrical energy, the production of more efficient electrical wires for distribution and transportation of energy becomes a necessity. At this context, a study of the Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si with the addition of 0,26%Ti was done to assess its performance when applied into power transmission networks. The alloy was obtained from electro conductive aluminum casting and the ingots by solidifying the metal in chill mold. Subsequently, the material was submitted to cold machining and rolling processes generating 4.0; 3.8; 3.0 and 2.7 mm diameters. Then the material as electrically and mechanically characterized (IACS and* UTS*, respectively). The testing determined that the effect of Ti addition is the increase of UTS for all diameters and decrease of IACS. The 3.0 mm diameter presented the greatest values of IACS, UTS and lower elongation (%). Another perspective shows that the macro structural analysis presented refined grains. It is possible that this behavior is due the formation of tri-aluminide that the titanium can form when combined with the aluminum.*

Keywords: Electrically conductive aluminum. Electrical conductivity. Strain testing.

1. INTRODUCTION

In 2010, according to the IBGE, a 1.3% of Brazilian households did not have electricity. In rural areas, this percentage reached 7.4%. The Federal Government program “Luz para Todos” (“*Light for All”*), already benefited about 14 million Brazilians was a driver of increased consumption of aluminum cables (ABAL, 2013).

Although electricity is responsible for revolution in humanity’s day life, is attributed to the design of wires and cables advances related to the transmission and distribution of electricity. As the production of cables, the most commonly used metals are – since the beginning – copper and aluminum. Although copper has a lower electric resistance and higher ductility compared to aluminum, the latter has the advantage of being lighter and being commonly used in distribution and transmission lines, but with bigger dimensions, allowing bigger gaps between support towers and consequent use of less towers. This promotes reducing installation costs (O SETOR ELÉTRICO, 2013). Despite this apparent advantage, aluminum has the disadvantage of not being effective in temperatures above 900ºC, because of this, the industry of production and distribution of energy has been seeking to develop materials with good performance at the 1500ºC. Enabling production of wires and cables that meets the requirements, such as, lightweight, good thermal and electrical conductivity, better thermal and creep resistance stability related to the Al-EC.

Of the various possible substitutes, the intermetallic alloys are prime candidates as a new generation of materials because they have properties that make them extremely attractive for structural use, particularly at high temperature.

The successful development of new engineering alloys based on intermetallic phases such as, in tri-aluminide (Al3X) where (X) is a transitional metal, exhibit low densities [20-50]% and these compounds are studied because of this potential advantages.

Of these compounds, the tetragonal phase (D022) Al3Ti ordinate, has been particularly interesting for the development of emerging structural materials for high temperatures applications due to its low density (3.36g/cm³) [3], a high melting point (1600K) [3], and excellent oxidation resistance [4].

2. MATERIALS AND METHODS

This paper can be divided into the following four [04] steps:

Step I – Obtaining of the base alloy (alloy I). : The alloy was obtained by direct casting in a silicon crucible at the Sub-laboratory of Metallography and Heat Treatment of the Federal University of Pará in a muffle furnace type, of the BRASIMET brand, based on the modified Al-EC. Stoichiometric calculations by mass percentage were made to determine the quantity of elements to be added to reach the desired chemical composition (0.05% Cu, [0.24 to 0.28] and 0.7% Fe % Si). For this procedure, an analytical scale of the OHAUS brand, Adventurer model, was used. Right after the crucible was removed from the furnace, argon was injected to remove impurities in the molten aluminum.

Step II – Addition of Ti (alloy II). : Similar to step I, the alloy was obtained by direct casting from Al-EC. Then the calculation of mass percentage for the alloy Al-0.05% Cu [0.24 to 0.28]% Fe-0.7% Si-0.26% Ti. In this step injection of argon was also performed to remove impurities from the aluminum.

Step III – Solidification, sectioning and macro-structural characterization. : For the solidification of the alloys I and II was adopted in metal chill "U" shaped (figure 1) as operating system. Ater the unmold, the obtained profiles (figure 1) were cut with a band saw. Once sectioned, the chemical analysis was performed in both alloys to assure a correct chemical composition. Then the macrostructural characterization was performed in the base segment.

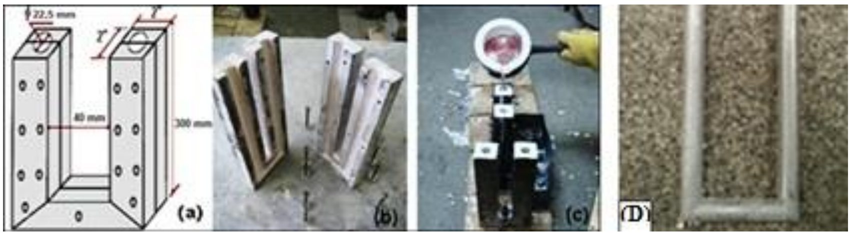

Figure 1 – (a) chill scheme; (b) chill; (c) alloy casting into the crucible used in this process; (D) specimen obtained in the solidification.

Step IV – Machining, laminating and characterization of the alloys. : Alloys I and II were machined on a lathe from its original diameter (22.5mm). to the diameter of 18.5mm and then submitted to the deformation process by cold rolling in a duo-electric rolling mill MENAC with circular section of different diameters, which generated wire shaped specimens with [4,0; 3.8; 3.0 and 2.7] mm diameters. Subsequently, the rolled wires were electrically characterized via Kelvin Bridge by MEGABRAS, MPK-2000 model, and mechanically via tensile test by KRATOS, IKCL1-usb model, generating electrical conductivity, tensile alongation and tensile elongation values.

Step V – Obtaining results. : To obtain the electrical properties, was adopted as reference to NBR-6814 standard, which describes, for electrical wires and cables, the method of measurement of the electrical resistivity of the conductor to direct current.

The wires electrical resistance were measured at temperatures not lower than 10ºC neither above 30ºC and the temperature was adjusted to 20ºC as recommended by the NBR 5118. After obtaining the results, from the reading of resistance of the specimens, the equation provided by the NBR 6814 was applied (Equation 1).

$$R_{20} = R_t\left(\frac{1}{1+\alpha(t-20)}\right) \qquad (1)$$

Where:

t = temperature at which the measurement was made, ºC;

R_t = resistance at TºC, in Ω;

R_{20} = correct resistance at 20ºC, in Ω;

α = coefficient of variation of resistance with temperature at 20ºC, specified by the standard for aluminum alloy.

With the resistance already fixed at 20 ° C, the resistivity is obtained, which is provided by Equation 2, obtained NBR 6815.

$$R_v = \rho_c \cdot A \qquad (2)$$

Where:

R_v = The electrical resistance CP per lenght unit at 20 ºC, in $\frac{\Omega}{\mathrm{m}}$;

ρ_c = volume resistivity ofCP at 20 ºC, in $\frac{\Omega\cdot\mathrm{mm}^2}{\mathrm{m}}$;

A = cross sectional area of theCP, in mm^2.

The results obtained are then converted into electrical conductivity, that is, into the International Annealed Cooper Standard (% IACS), the international electrical conductivity standard corresponding to the conductivity presented by a 1m copper wire with 1mm² cross section at 20ºC, by equation 3:

$$\varphi = \frac{\rho_{Cu}}{\rho_{Al}} \tag{3}$$

Where: φ = the electrical conductivity of a wire in IACS;

ρCu = the electrical resistivity of copper in $\frac{\Omega \cdot mm^2}{m}$;

ρAl = the electrical resistivity of aluminum in $\frac{\Omega \cdot mm^2}{m}$.

After the cold deformation of the alloys and obtaining of the desired diameters, the specimens were subjected to mechanical testing. Tensile tests followed the NBR 6810 standard for electrical cables and were executed on three specimens with 20 cm of length for each diameter mentioned in this paper. For this paper it is noteworthy that based on the tensile tests, tensile yield strength data was collected, as well wire Elongation and microcavities.

From the griding and polishing of the extracted ingot section, the macrostructures of the alloys are revealed in specimens as cast. Thus, the polished surfaces of the specimens are attacked by immersion in Poulton solution [12mlHCl (concentrated), 6 ml HNO3 (concentrated), 1 mL HF (48%), 1 ml H2O], made according to standard techniques in metallography (ASM International, 2004). After etching, the surfaces of the specimens were washed in abundant running watter, rinsed with acetone and dried with a hot air dryer

3. RESULTS AND DISCUSSION

3.1 Chemical composition analysis

The Table 1 have the results for the chemical compositions analysis of the samples obtained from the Al-0.7% of Si alloys with add on of 0.26% Ti later. The readings of the composition were obtained through optical spectrometer analysis, as aforementioned, assuring that the alloys have the correct amount of elements.

Alloy	%Cu	%Fe	%Si	%Ti	%Zr
Base	0.0498	0.2513	0.7238	-	-
0.26% of Ti	0.0524	0.2563	0.6818	0.2556	-

Table 1 – Chemical composition of the aluminum alloys.

3.2 Macrostructures

According with the phase diagram the formation of Al_3Ti occurs with additions above 0.15%. Stefanescus (2002) states that the solid Al_3Ti with temperature over the invariant peritectic point shows a heterogenic core, justifying the refinement potential of the Ti in Al alloys. That way, through the macrostructures presented in the Fig. 2, it is observed that the Ti refined the base alloy grains more efficiently, suggesting that after the solidification process, the Al_3Ti particles are numerous, on the primary particle shape.

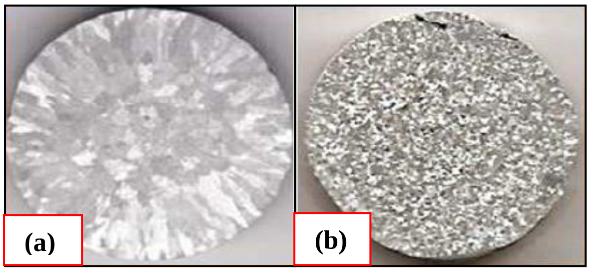

Figure 2 – Gross fusion macrograph: (a) grãos equiaxed grains Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si alloy; and (b) thin granulation chill grains for the 0.26%Ti base alloy.

3.3 Electrical characterization

According with Figure 3, it is observed that the electrical conductivity [φ (%IACS)] of the base alloy 0.7% of Si it was not prevailed with the additions of Ti. This result allows the consideration that the particles on tri-aluminide Al3Ti initially into ordered DO22 shape that feature the capacity of refining grains and has the characteristic of low electrical conductivity. However, the values plotted in Figure 3 shows the diameter 3mm with higher conductivity values for both cases. This diameter presents greater accumulation of cold work and, although more strained, shows as the best electricity conductor. This apparent misinterpretation, may be explained by an intensified dynamic recovery.

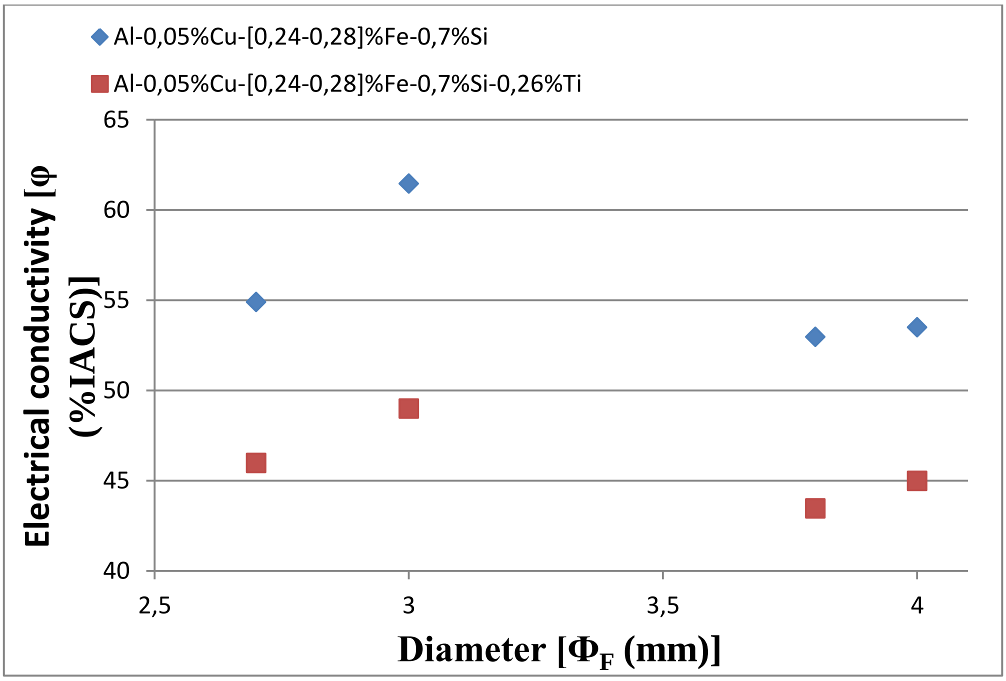

Figure 3 – Comparative of electrical conductivity values [φ (%IACS)] for the Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si and Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti alloys, Φ] [2.7; 3.0; 3.8 and 4.0] mm diameters.

3.4 Mechanical characterization

According to the figure 4.9, it is noticeable that the ultimate tensile strength (UTS) of the base alloy with 0,7% of Si was surpassed with additions of Ti, leading to the conclusion that the greater grain refinement potential associated with the Ti lead to a increase of the traction resistance limit of the alloy. Furthermore, it is noticeable, for the alloys, that the [Φ] 3.0 mm diameter wire overshadows all other wires tested, possibly due the higher level of cold work that it was submitted.

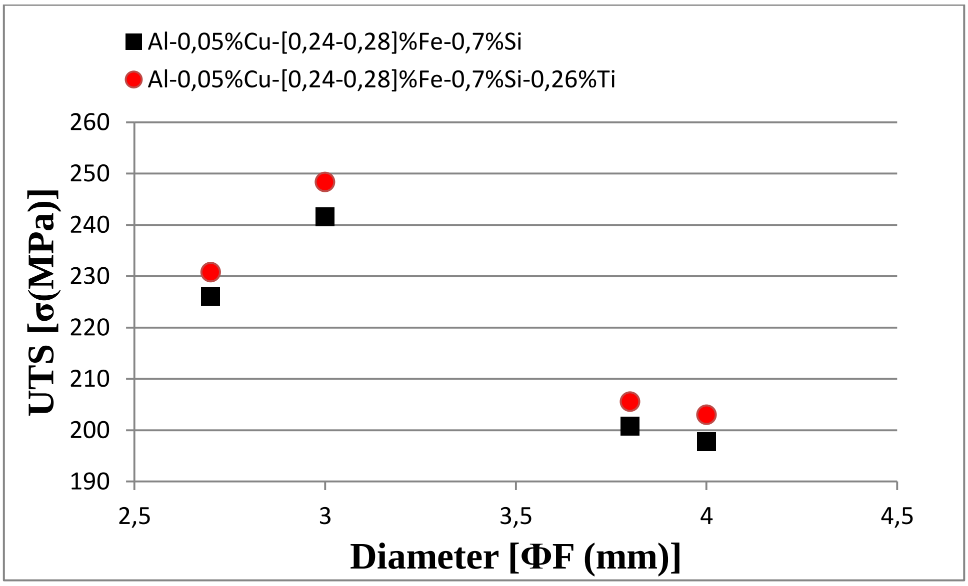

Figure 4 – Comparative between UTS values [σ (MPa)] for Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si and Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti alloys, [Φ] [2.7; 3.0; 3.8 e 4.0] mm diameters.

3.5 Stretching of the base alloy with 0.7%si and 0.26%t

The table 2 shows data for the Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si and Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si-0,26%Ti alloys, both without heat treatment (STT), for: elongation values [δ (%)] for the diameters [Φ] of [2.7; 3.0; 3.8 e 4.0] mm.

	Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si	Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti.

Diamemter [Φ_F (mm)]	Elongation [δ (%)]	Elongation [δ (%)]
2,7		
3,0	4,88	3,37
3,8	4,82	3,14
4,0	5,68	4,71
	5,58	4,69

Table 2 – Relation between Elongation values [δ (%)] for [Φ = 2.7; 3.0; 3.8; 4.0] mm diameters of Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si STT and Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti alloys.

The elongation values [δ (%)] are plotted on the graph shown on Fig. 5, where is shown the values for the Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si and Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si-0,26%Ti alloys.

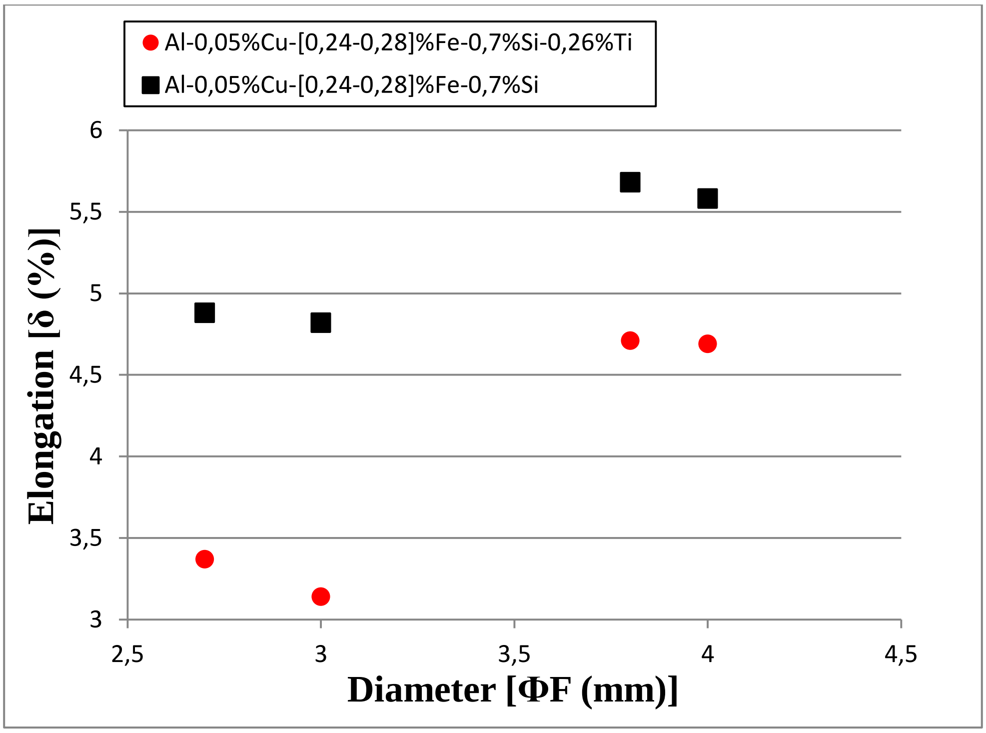

Figure 5 – Relation between elongation values [δ (%)] for Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si and Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti alloys, [Φ] [2.7; 3.0; 3.8 e 4.0] mm diameters

It is possible that the low levels of coalescence of the microcavities [smaller (L/W) ratios] presented by this profile are consequence of the dynamic recovery phenomenon adjusted to the deformation matrix used for obtaining it.

According to the Fig. 5, the behavior of the grow of the elongation values [δ (%)] presents a coherent tendency, because while UTS decreases [MPa] **f**ig. 4, the elongation [δ (%)] increases. This behavior is observed in the Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si and Al-0,05%Cu-[0,24-0,28]%Fe-0,7%Si-0,26%Ti alloys.

It is noticeable that the highest UTS value (241.54 MPa) – obtained by the de 3.0 mm diameter – have a lower value of δ= 4.82% and ϑ= 1.349, indicating that this material, in this given condition, has higher rigidity, and consequently, is more resistant to deformation; relation presented on fig. 5.

Regarding the base alloy, note that the inclusion of 0.26% of Ti generated greater resistance limits values for all the diameters fig. 4, highlighting the wire diameter 3.0 mm (248.34 MPa), that also has lower values for o δ= 3.14%, as for ϑ= 1.285. Possibly indicating that the material, at the given work conditions, provide greater rigidity and consequently absence of the coalescence phenomenon of the cavities, and possibly being more resistant due the flow conditions on practical applications.

4. CONCLUSION

It has been found that the titanium has a higher grain refining capacity for the base alloy (Al-0.05%Cu-[0.24 to 0.28]%Fe-0.7%Si).

Regarding the electrical properties, the addition of 0.26%Ti did not resulted in enhancement for the Al–0.05%Cu-[0.24-0.28]%Fe-0.7%Si alloy. Thus, refined grains did not contributed to contribute to increase the electrical properties.

As for the mechanical properties, the Ti helped to increase the UTS. The refined grains contributed to this increase, comparable to the precipitate incoherence aspect for the aluminum matrix;

For the structural properties, the lowest elongation for the Al-0.05%Cu-[0.24-0.28]%Fe-0.7%Si-0.26%Ti alloy [Φ= 3,0 mm] may be related to the grain refining potential of the Ti, also changing the microcavities ratio. Possibly, this behavior is related to a lower discordance movement.

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