



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

**COB-2019-2279**

**CHARACTERIZATION AND ANALYSIS OF AL-6%MG ALLOY  
MODIFIED WITH 0.30% ZR AND SUBJECTED TO STRESS RELIEF OF  
400 °C/ 1H**

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**Abstract.** *The growing demand for electricity requires the production of increasingly efficient electrical cables for transmission and distribution of energy. This work aims to analyze the mechanical and electrical characteristics of Al-6% Mg alloy with the addition of 0.30% of Zr and the influence of the thermal stress relief treatment on these characteristics. The alloys were cast in a muffle furnace and cast in a copper mold (section of the Properzi wheel) cooled in water. Cross sections of each ingot were obtained and passed through sanding and polishing processes for metallographic characterization. From each ingot, the reference samples were cut and machined to 9.5mm in diameter and cold rolled until they reached the 3mm diameter. Afterwards, two groups were separated: those without heat treatment and those treated thermally, the heat treatment was at 400 °C for 1 hour. The tensile test was performed for mechanical characterization and for electric characterization the electric resistance test was performed. The electrical conductivity test was performed and due to the amount of magnesium solute the alloys obtained an average electrical conductivity value of 30.34% IACS. The limits of tensile strength and elongation of the alloys before and after the heat treatment were evaluated. This treatment caused ultimate tensile strength loss and real strain gain of the samples. In the curves resulting from the tensile tests, in all the alloys, were observed the Portevin-Le Chatelier phenomenon.*

**Keywords:** *Aluminum alloys, Stress relief, mechanical and electrical characterization.*

## 1. INTRODUCTION

The cable industry for the transportation and distribution of electric power has grown in recent years, mainly aluminum alloy cables, thanks to good mechanical properties combined with high electrical conductivity and reduced weight of these cables. These properties can be improved and combined with others, such as thermoresistance, as well as contributing to the production of more efficient and cheaper energy transmission and distribution lines. The understanding of the various alloying elements and their effects on the structure of the material is essential to the purpose. In view of the technological development, the structure of the material is of importance, considering that it is correlated with the mechanical, physical and chemical properties of the material of the part.

But aluminum alone does not have favorable characteristics for use. Ultra-pure aluminum with a purity of 99.9999% has a tensile strength limit of only 12 MPa, while at purity levels of 90.0% this value jumps to 40 MPa and some precipitation-hardened aluminum alloys can reach strength values as high as 625 Mpa, such a conclusion is seen in Russel and Lee (2005).

Magnesium is one of the few elements with high solid solubility in aluminum, with its equilibrium around 15% at 450 °C, although this solubility approaches zero at 20 °C. The phase equilibrium of Al-Mg offers a good fall resistance

potential, but the effect of these precipitates is small. Consequently, the primary effect resulting from magnesium additions on aluminum will be supported by the solid (metastable) solution that was treated in Kaufman and Rooy (2004).

The presence of magnesium significantly reduces alloy density ( $2.65 \text{ g/cm}^3$ ) and reduces aluminum stacking failure energy, which causes an increase in dynamic recovery temperature, allowing the alloy to retain cold working properties at higher temperatures before recovery and recrystallization occur. Magnesium alloys in the order of 4% usually do not form  $\text{Mg}_2\text{Al}_3$ , although it may precipitate on grain boundaries if the metal is kept at temperatures of  $120^\circ \text{C}$  to  $200^\circ \text{C}$ , which may cause intergranular corrosion, this can be found in Kaufman and Rooy (2004).

Aluminum alloys with additions of group IV elements of the periodic table (Ti, Zr and Hf), present potential as structural materials at high temperatures, because they have low solid diffusivity, form high symmetry compounds, have low density, high point and low precipitate / matrix divergence (Kumar, 1990; Knipling et al., 2007). Among these elements, the addition of Zr to Al has low solid solubility, decreased solubility (Knipling et al., 2007) and precipitates as the metastable  $\text{Al}_3\text{Zr}$  with L12 structure. These particles provide hardening of the material for periods greater than 400 h (Knipling et al., 2006), which is not achieved by other additions, such as Ti, Sc, Er or Hf.

## 2. MATERIALS AND METHODS

The methodology used in this work was to divide the samples into two groups: without heat treatment and with heat treatment. In the first step after the stoichiometric calculation and the melting of the alloying elements, the ingots for each alloy were sectioned. From the ingots were obtained chemical composition and macrostructure. The material obtained from the slicing of the ingots was machined to the diameter of 9 mm. In the second step, the material was cold rolled gradually to the 3mm diameter where two groups of samples were divided, the samples without heat treatment and those treated thermally. The heat treatment was  $400^\circ \text{C}$  for 1 hour in order to induce tension relief. The two groups of samples then passed the conductivity and tensile tests.

### 2.1. Casting and solidification

The alloys were obtained by direct casting where an aluminum conductor was fused. The magnesium element was used in its pure form. The zirconium element was used from an Al-10% Zr alloy. The masses of each element were determined by stoichiometric calculations, considering their respective percentages in each alloy. In the cutting of the Al-EC the band saw was used. Subsequently all the elements were weighed in the digital scale and then melted in the muffle furnace.

After confirmation of complete melting of the metals, the melting pot was removed from the furnace, which was then homogenized by melting the metal by hand using a spatula painted with kaolin solution ( $\text{Al}_2\text{O}_3 + 2\text{SiO}_2 + 2\text{H}_2\text{O}$ ). After homogenization, the inert gas (argon) was injected into the molten alloy through a stainless-steel tube connected to a  $10\text{m}^3$  cylinder. Argon was injected into the molten metal to remove low density gases and impurities, which are segregated by forming a slag layer on the bath surface, which was immediately removed by a steel spatula painted with kaolin solution. The solidification was started with the removal of the sample for chemical analysis (control sample).

The solidification stage of the alloys was through a copper mold corresponding to the segment of the properzi wheel (shown in Fig. 1.a), provided by the company ALUBAR. This mold was suitably sealed (shown in Fig. 1.b), and immersed in water (shown in Fig 1.c). The whole arrangement was designed so that the process had a high rate of cooling (quenching). The molten material is deposited in the copper mold (shown Fig. 1.d). Two ingots were obtained, one for each alloy composition, in which they present approximate length of 160 mm (shown in Fig 1.e).

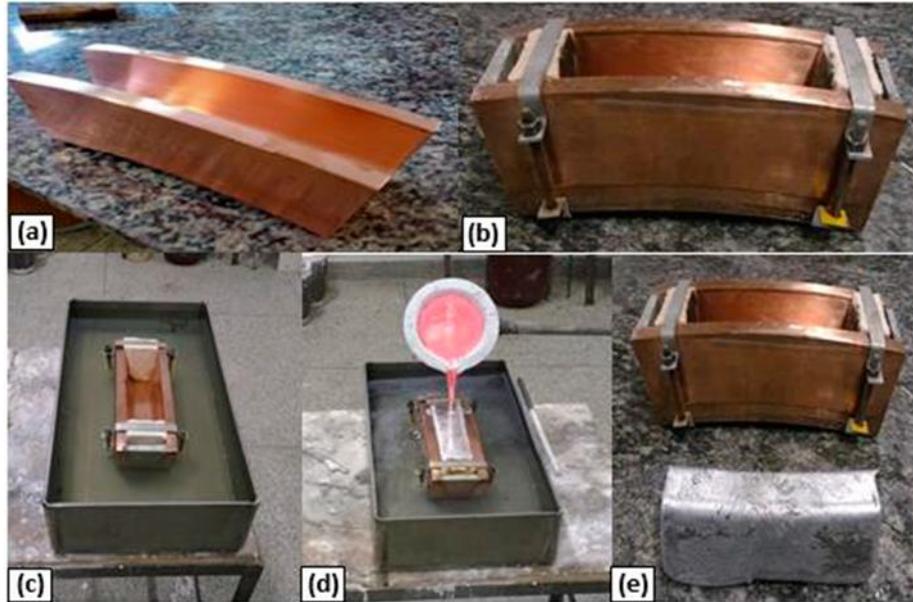


Figure 1. Wheel cast suitable for ingot solidification. (a) Properzi wheel segment, (b) properly sealed mold, (c) water immersed mold, (d) ingot casting and (e) solidified alloy. Source: GPEMAT GROUP.

## 2.2. Heat treatment

After obtaining the sectioned and machined material, the cold rolling was done, thus obtaining yarns with the diameters of 3 mm, from the 9.5 mm diameter material. The procedure was carried out in a "duo electric" laminator of circular cross-section of different diameters. The four wires resulting from the rolling were divided into two groups, the first one was not heat treated, while the second was subjected to a treatment of 400 ° C for 1 hour in the greenhouse brand NEVONI, in order to demonstrate the effect of the stress relief in the electrical and mechanical properties of Al-6% Mg and Al-6% Mg-0.30% Zr alloys.

## 2.3. Metallographic characterization

The macrostructures of the alloys were developed according to standard techniques in metallography following the sanding and polishing steps. In the sanding process the sequence of the grit abrasive used was 80, 120, 220, 320, 400, 600, 800, 1000, 1200, and 1500. After this step, was performed the polishing by oxide polishing following the sequence 1  $\mu\text{m}$ , 0.5  $\mu\text{m}$  and finishing in the 0.3  $\mu\text{m}$ . The chemical attack was performed by immersion with Keller metallographic reagent (2ml HF + 3ml HCl + 5ml HNO<sub>3</sub> + 190ml H<sub>2</sub>O). The chemical composition of the alloys was obtained through a Q4 TASMAN optical spectrometer.

## 2.4. Electrical and mechanical characterization

The electrical and mechanical tests were carried out on 3 mm diameter wires obtained after the machining and rolling of the specimen obtained in the solidification process. In the electrical characterization, the test bodies were submitted to the tests with the objective of evaluating the electrical resistivity with the aid of a multi-ohmmeter (kelvin bridge) of the manufacturer MEGABRÁS. The electrical resistivity tests were performed according to the norms NBR 5118 (2007), NBR 6810 and NBR 6815 (1981b). After the electrical characterization, the specimens were submitted to the mechanical test, in a KRATOS traction test machine, model IKCL1 - USB. The tensile tests were performed according to the norms for electric cables, NBR 681, and metallic materials, NBR 6892, running them in three samples with 20 cm for each diameter.

## 3. RESULTS AND DISCUSSIONS

### 3.1. Chemical composition

Table 1 presents the composition of the alloys Al-6% Mg and Al-6% Mg-0.30% Zr, in this table it can be verified that the obtained chemical compositions are in agreement with the values that were proposed for analysis in this work.

Table 1. Chemical composition of the alloys. Source: GPEMAT GROUP.

ALLOY	ALLOY COMPONENTS (% MASS)		
	Fe	Mg	Zr
Al-6%Mg	0.134	5.853	0.002
Al-6%Mg-0.3%Zr	0.150	5.852	0.296

### 3.2. Macrostructure of alloys as castings

Figure 2 presents the structures obtained during the solidification process, they were analyzed macroscopically in order to make a comparison between the alloys Al-6%Mg (shown in Fig. 2.a) and Al-6%Mg-0.30%Zr (shown in Fig. 2.b).

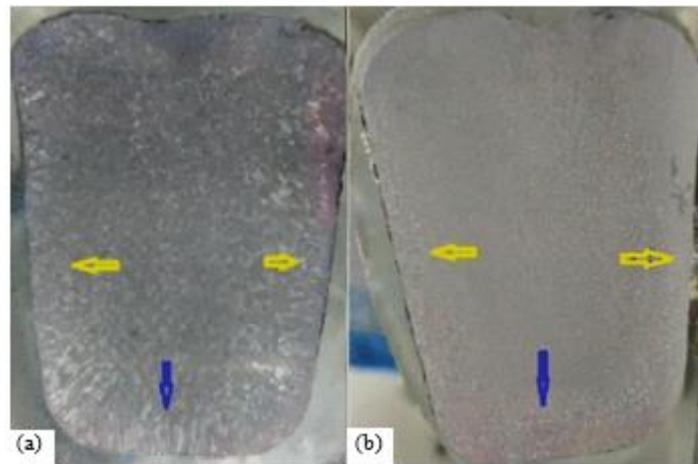


Figure 2. Copper cast solidified alloy macrostructures. a) Al-6%Mg Alloy; b) Al-6%Mg-0.3%Zr Alloy. Source: GPEMAT GROUP.

In the base alloy Al-6% Mg, seen in Fig. 2.a, we notice the tendency of columnar zones in the metal / mold interface (yellow and blue arrows), but inside the material there is the presence of equiaxial grains. For structure present in Fig. 2.b, base alloy with 0.30% zirconium addition, showed changes in the microstructure of the material, the addition of zirconium caused the disappearance of grains with columnar tendencies in the metal / mold interface, forming a homogeneous structure and highly refined.

The magnesium content added to the alloys was responsible for the grain refining observed, with the addition of zirconium aided when it reached the value of 0.30% Zr. This grain refining behavior when mixed Mg and Zr has already been observed in Santos (2010).

### 3.3. Electric conductivity

The electrical conductivity of modified Al-6% Mg alloys with 0.30% Zr contents is presented in Tab. 2 without heat treatment.

Table 2. Electrical conductivity test result for alloys without heat treatment. Source: GPEMAT GROUP.

ALLOY	ROOM TEMPERATURE (°C)	ELECTRICAL RESISTANCE (mΩ)	CORRECTED RESISTANCE TO 20°C (mΩ)	ELECTRICAL RESISTIVITY (Ωmm <sup>2</sup> /m)	ELECTRICAL CONDUCTIVITY (%IACS)
Al-6%Mg	26.3	2.48	2.42	0.05718	30.15
Al-6%Mg-0.30%Zr	26.2	2.53	2.47	0.05836	29.54

The two alloys had low values of electrical conductivity due to the amount of solute inserted in the alloy. The Mg element may have attributed to the alloys the low values of electrical conductivity when compared to electroconductive

alloys, thus not being indicated for the application as conductors of energy. The addition of zirconium caused negligible variations.

The samples that received the heat treatment were subjected to a temperature of 400 ° C for one hour. The results can be observed in Tab. 3, which has the values of electrical conductivity for the alloys studied in this work.

Table 3. Electrical conductivity test result for alloys with heat treatment. Source: GPEMAT GROUP.

ALLOY	ROOM TEMPERATURE (°C)	ELECTRICAL RESISTANCE (mΩ)	CORRECTED RESISTANCE TO 20°C (mΩ)	ELECTRICAL RESISTIVITY (Ωmm <sup>2</sup> /m)	ELECTRICAL CONDUCTIVITY (%IACS)
Al-6%Mg	26.1	2.39	2.38	0.05515	31.26
Al-6%Mg-0.30%Zr	25.7	2.48	2.42	0.0573	30.09

### 3.4. Mechanical properties

Figure 3.a presents the stress versus strain graph resulting from the untreated alloy tensile test and Fig. 3.b shows the results of the same, but heat treated, test.

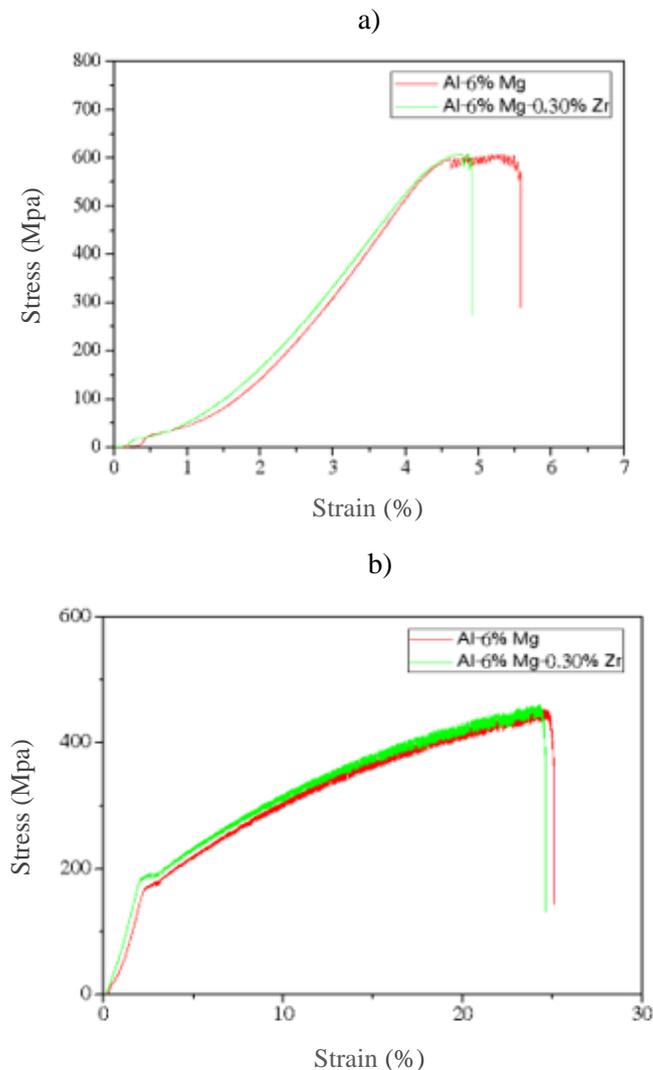


Figure 3. Real strain x real stress graph of the alloys in a) without heat treatment and b) heat treated. Source: GPEMAT GROUP.

Figure 3.a shows minor ductility loss for the alloy with 0.30% Zr addition probably due to the increase of solute in the alloy. The results show the effect of Portevin-Le Chatelier during the plastic deformation zone of the material. In the alloy without Zr addition, the range where the effect occurs is much longer and the addition of Zr tends to inhibit the effect. Figure 3.b, the yield limit of 0.30% Zr alloy showed little variation to that of the alloy without Zr addition.

The Portevin-LeChatelier effect was observed in alloys with and without heat treatment, but the alloy in which heat treatment was performed had an extension in the region of plastic deformation, region of occurrence of the effect. This effect was also observed in Chibane and Ait-amokhtar (2013).

Figure 4.a shows the tensile and Fig. 4.b shows the elongation strength results for Al-6% Mg and Al-6% Mg-0.30% Zr alloys with and without heat treatment. Alloys that are equivalent to a traction equals to a maximum rate of 2.5% may be neglected. As the alloys with the processing results are also equivalent to each other with respect to the maximum of 4.1% in the values.

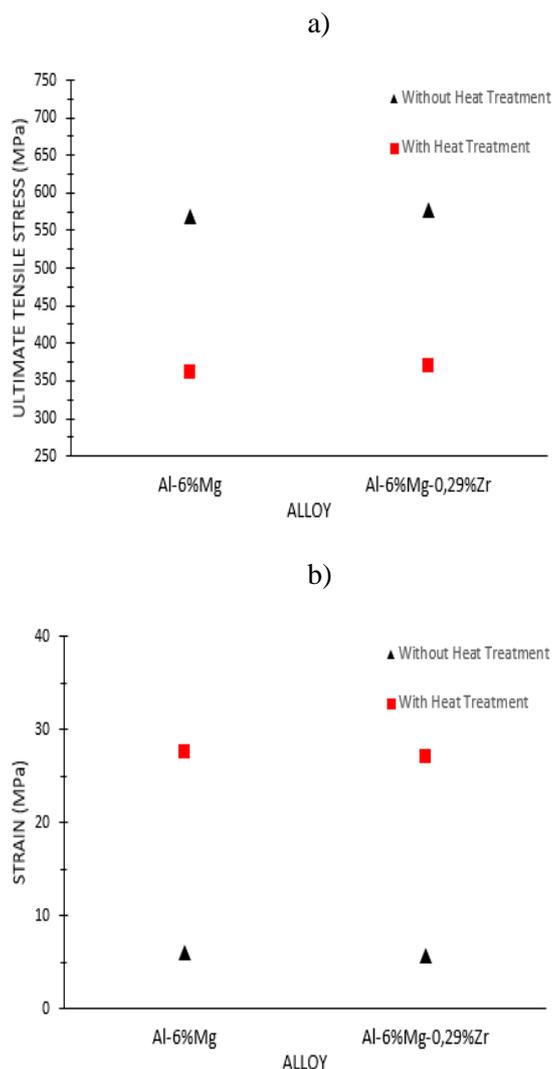


Figure 4. Comparative graph of ultimate tensile stress in a) and strain in b) for the alloys. Source: GPEMAT GROUP.

It was observed that alloys without heat treatment had better tensile strength values when compared to alloys with stress relief treatment, in which the heat treatment generated an average loss of tensile strength of 36.48%. The elongation of the alloys was little influenced by the addition of zirconium, but with great influence of the heat treatment. The elongations of the heat-treated alloys obtained average gain of 21.22% in real deformation. Both results may be linked to the fact that the heat treatment has undone one of the hardening mechanisms, in this case the cold work, thus impairing the mechanical characteristics of the material.

#### 4. CONCLUSIONS

Considering the methodology developed in the present study to observe the structural characterization for alloys without heat treatment and the electrical and mechanical characterization of alloys without or with heat treatment, it is concluded:

For the macrostructural characterization of the alloys Al-6% Mg and Al-6% Mg-0.30% Zr, the macrostructure of the material was completely refined due to the magnesium and zirconium value added.

In the analysis of the electric behavior of the Al-6% Mg and Al-6% Mg-0.30% Zr alloys with heat treatment, it can be seen that for the untreated samples, 6% Mg, with the additions of zirconium did not significantly alter the electrical conductivity values of the alloys. In the case of the samples with treatment this generated inexpressive gains of electrical conductivity in the studied alloy.

When analyzing the mechanical behavior of Al-6% Mg and Al-6% Mg-0.30% Zr alloys with and without heat treatment, it was observed that in the untreated samples the addition of zirconium did not cause any perceptible changes to the limit of tensile strength and elongation values. However, in the untreated samples this generated loss in the limit of tensile strength and gain in the elongation values of the alloy studied.

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