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Proposed solution for random characteristics of aluminium alloy wire rods due to the natural aging

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Abstract

In the last 50 years in the worldwide market for power transmission cables, there has been a tendency to replace aluminium cables electrical grade (EC) with steel cables by fully aluminium alloy (AAAC). The advantage in using cable AAAC is mainly economic (least amount of support structures and maintenance), addition to the elimination of the problems of galvanic corrosion and improved abrasion resistance. In order to obtain better mechanical properties, respect to the pure aluminium, aluminium alloyed with magnesium and silicon (AA6XXX series) is used, which by a combination of cold working and heat treatment allows obtaining greater mechanical strength without affecting too much the electrical conductivity. In this development it has worked with AA6101/6101M alloy. The manufacturing of aluminium alloy wire rods for such applications, using the conventional process Properzi, requires heat treatment of solubilized, continuous or discontinuous (batch). During the waiting time of two months or more, the wire coils are exposed to natural aging at room temperature, entering into the wiredrawing machines with different mechanical properties. The wires obtained by the traditional method of manufacture in Argentina, through the wiredrawing, result in significantly higher mechanical properties, not complying with the standards. Furthermore many breaks occur mainly when a high tensile strength wire is processed for wire 2 mm in diameter or less. In the proposed method, a part of the initial wiredrawing is replaced by cold rolling and a subsequent partial aging. The results obtained in this study allow us to conclude that in the proposed process better properties and mechanical integrity are achieved than the traditional process, maintaining the electrical conductivity.

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Keywords: Aluminium alloy, natural ageing, cold work

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1. Introduction

Electrical conductor's aluminium alloy wires are mainly used in transmission lines of high voltage. The main advantages in using these cables regarding electrical grade aluminium with steel core are mainly economic (less amount of support structures and maintenance) since all the problems related to the inhomogeneity of the steel core wire galvanic corrosion are eliminated. They also have a better abrasion resistance, which makes them more suitable for supporting the assembly manipulations [Bunte et al. (2008)] [Rheinboldt Neto et al. (2000)].

In order to obtain better mechanical properties, compared to the pure aluminium, without affecting the electrical properties, aluminium alloyed with magnesium and silicon (AA6XXX series, specifically alloys 6101) due to this series has greater strength than electrical grade aluminum, without affecting the electrical conductivity too much.

The aluminium alloy wires (AAAC) are manufactured from rolled wire rod of about 10.0 mm in diameter. Generally, since they are heat treatable alloys, prior to drawing, the wire rod is subjected to heat treatment of solubilized, which is primarily intended to dissolve all the Mg and Si, to obtain a coil with good drawability and good response to artificial aging.

However, from the moment the solubilized treatment ends, the natural aging of the material begins to occur, while the properties of the wire are changing.

Both the mechanical strength and electrical properties depend primarily on the degree of plastic deformation and its interaction with the precipitates in the matrix, and the type and content of alloying elements in solid solution as well as the present precipitates.

The aim of this study is to subject the rod wire to a change in the first stage of cold forming, wiredrawing along with intermediate partial aging instead of cold rolling, in order to obtain AAAC type cables with better final properties, seeking to find an alternative way to manufacture, thus neutralizing the variability in the properties caused by the use of wire rods with different storage times after solubilized on site.

In particular this work was performed on wire rods of alloy 6101M 9.50 mm in diameter produced by ALUAR at its plant in Puerto Madryn.

1.1. Basic characteristics of aluminium alloys 6XXX series

As we have seen in the previous work [Bunte et al. (2008)], this series is composed mainly of Al-Mg-Si and is used in electrical applications (electrical conductors) where an appropriate combination of properties such as high strength, high conductivity and optimal ductility are required. Figure 1 shows the effect of alloying elements on the electrical conductivity of aluminium. To achieve these requirements thermomechanical treatments are used [Altenpohl (1998)].

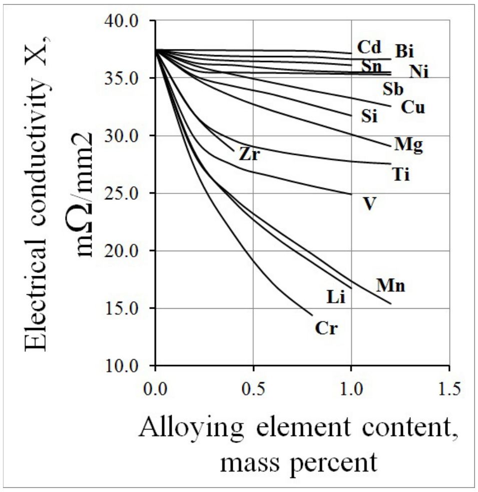


Fig. 1. Electrical conductivity vs. Alloying elements content.[Bunte et al. (2008)]

The microstructure of Al-Mg-Si alloy is a α solid solution matrix and numerous intermetallic compounds such as Mg_2Si. This phase has a significant effect on the properties, as precipitation hardening effects are attributed [Porter and Easterling(1992)]. Their solubility in solid solution in the aluminium matrix is temperature dependent (Figure 2) and therefore belong to the type of heat treatable aluminum alloys [Aluminium Handbook (1999)].

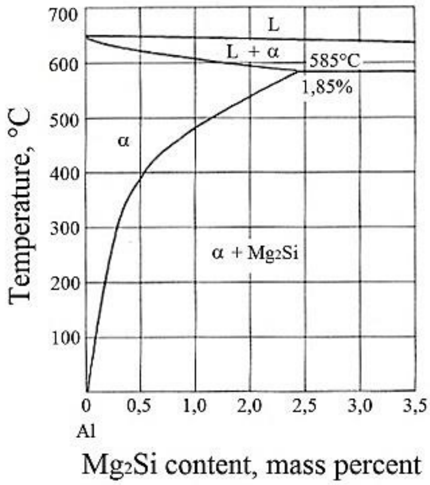


Fig. 2. Pseudobinaryphasediagram(Al-Mg_2Si). [Bunte et al. (2008)]

It was also seen on previous work that partial aging of the mechanically deformed solid solution effectively helped to improve the final mechanical characteristics.

The slope of the hardening curve was higher in the case of partial intermediate aged material, by having more particles per unit volume that anchored more dislocations produced by subsequent deformation. Finally higher elongation in the tensile test at break was obtained, as a result of better integrity of the resistant cross section.

The type of deformation obtained by cold pilgering gave a structure with such internal energy that in the partial aging, with time and temperature conditions substantially lower than normal, the kinetics of evolution of precipitation of Mg_2Si was fast enough to almost complete the process. That is why after, to a final diameter, final aging conditions were exaggerated [Aluminium Handbook (1999)].

The torsion test showed very high results, since instead of exceeding the minimum 8 twists with values between 12 and 15, higher values were reached. This is only possible if the integrity of the mass is free of micro cracks or other flaws of continuity.

We should not forget that to manufacture high quality aluminium cables, the steps involved in its production must be carefully controlled [Chia (1978)]. The main heat treatments used include; solubilization, annealing, quenching and aging, and are the key to obtain an optimal mechanical working (cold drawing, rolling, etc.) [Nonferrous Wire Handbook (1981)] [Iraizoz (2005)]. High conductivity is obtained by treatments which achieve the maximum precipitation of Mg_2Si as crystalline defects, impurities and alloying elements in solid solution increases the resistivity of the metal. Furthermore the mechanical strength depends on the type and amount of precipitate produced on the aluminum matrix [Mondolfo (1976)] [Iricibar et al. (1978)] [Dieter (1976)].

Currently, one of the most used alloys in high voltage conductors is the AA 6101 T65 which has an electrical conductivity of 56.5% IACS and Rm 300 MPa.

The range of chemical composition that corresponds to the used alloy, according to IRAM 681, is shown in Table 1 [Norma IRAM 681 (1996)].

Table 1: 6101 (IRAM 681) – Chemical composition

Name	Mg	Si	Fe	Cu	Al
6101	0.35-0.80	0.30-0.70	0.50	0.10	Balance

In Table 1 it can also be noted that there is a wide range of chemical compositions of main alloying elements, that is why there are 6101 light alloys (designated 6101) and 6101 heavy alloys (called 6101M). Due to problems that often occur during wiredrawing, the heavy alloys receive different final heat treatment that the light alloys.

1.2. Alloying elements

Alloying elements in solid solution affect the resistivity and this effect greatly differs for different elements. The elements that increase the resistivity are the transition elements as Zr, V, Ti, Cr (Figure 2). On the other hand, in the aging, a drop in resistivity was observed which is attributed to the emergence of compounds incoherent with the matrix. In conclusion, we can say that the alloying elements in solid solution have more effect on the resistivity than when they precipitate into incoherent second phases [Iricibar et al. (1978)].

2. Experimental procedure

The present work had the following assumptions:

- Replace deformation through cold pilgering step prior to partial aging, by conventional cold rolling.
- Find partial aging conditions that allow more flexibility during the process by the time of combining heat treatment with the final deformation.
- Wire drawing under similar conditions to the industrial practice.
- Check the relationship between the mechanical properties and electrical properties.
- Check microstructure of the final wire using scanning electron microscopy (SEM).

The used raw material, a 9.70 mm diameter wire rod provided by Aluar SA, was laminated to an intermediate diameter (60 to 70% cross section reduction). Then it was made a partial aging at 200°C for 1 hour interval.

Then it was drawn to two different final diameters, 2.00 mm (65-75% cross section reduction) and 3.00 mm (80-90% cross section reduction).

Both wires were aged in two stages. In both steps the same intermediate aging parameters were used. The first stage and the second were identified as TT1 and TT2, respectively.

2.1. Experimental Techniques

A series of 6101M alloy samples were processed according to the traditional procedure and another series of the same alloy were processed according to the alternative procedure. The following experimental techniques were applied to samples taken before and after each stage. The following tests and studies were conducted:

- Optical and Scanning Electron Microscopy
- Tensile test [Norma IRAM766 (1972)]
- Resistivity test
- Torsion test

3. Results

Due to the raw material is the same as used in previous work, only the results obtained are shown on the wire after the final drawing to the diameters of 2 to 3 mm. For reference is recorded data wire again.

3.1. Wire rod

3.1.1. Chemical composition

The chemical composition of the used alloy in this work is shown in Table 2. The chemical composition of the rod wire was determined by the Optical Emission Spectrometry procedure (OES) [Norma IRAM 681 (1996)].

Table 2: Chemical composition of the alloy 6101M (% mass)

Alloy	Mg	Si	Fe	Cu	B	ΣCr+Ti+V+Mn	Al
6101M	0,575	0,490	0,210	0,0005	0,0028	0.0144	Balance

3.1.2. Microstructure

The 6101M alloy wire rod had a microstructure of equiaxed recrystallized grains with size difference between the periphery and the center of the sample. The grain size in the center is ASTM 4 to 5 while the surface is ASTM 6 to 7.

It can be seen at least three different morphologies of precipitates, stick, faceted and globular, which dimension is around 50 μm approx. The observed precipitates in Alloy 6101M are more globular than in 6101.

3.1.3. Mechanical and electrical properties

The results of mechanical strength and electrical conductivity for the wire rod are shown in Table 3.

For the determination of the mechanical properties, the procedure indicated in the IRAM 766 standard was applied [Norma IRAM 766 (1972)] and 50 mm reference distance was taken for determining of the elongation.

For resistivity measurements, a technique called "4-wire" on meter-long samples was performed, using an Agilent 6611C current source. The data in mV were collected with an Agilent multimeter, model 34401.

The results were reported as conductivity.

Table 3: Mechanical strength and electrical conductivity of the alloy 6101M.

Alloy	Rm [MPa]	Electrical conductivity [%IACS]
6101M	202	50.5

3.2. Final wire

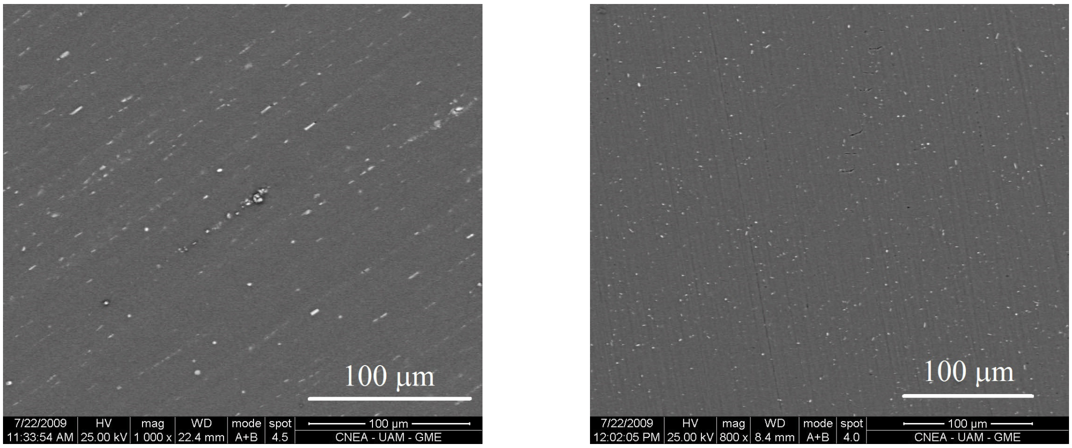
3.2.1. Microstructure

Samples of the final wire, both longitudinal and transverse, were analyzed by electron microscopy. The samples show similar grain morphologies to those obtained in previous work, deformed and oriented in the rolling direction at all stages of deformation (Figure 3).

The observed precipitates by optical microscopy do not show any change neither in its shape, morphology and distribution nor with the deformation or with the heat treatment (Figures 4-5).

The type and the chemical composition of the found precipitates were the following:

- AlFeSi (80/15/5)
- AlTi (57/43)
- AlFeSiMg (88/4/4/4) [Martinovaand Zlateva(2002)] [Bonmarin and Adenis (1969)].



a b

Fig. 3. (a) Alternative process (final cold drawing), longitudinal micrography; (b) Transversal micrography

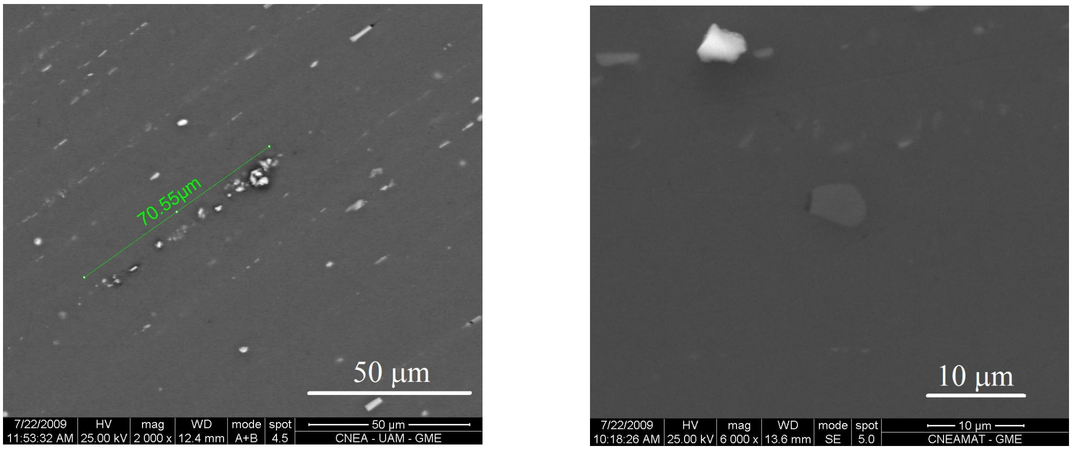


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Fig. 4. (a) Alternative process (final cold drawing), AlTi precipitates; (b) Morphology of AlFeSi precipitates, globular type

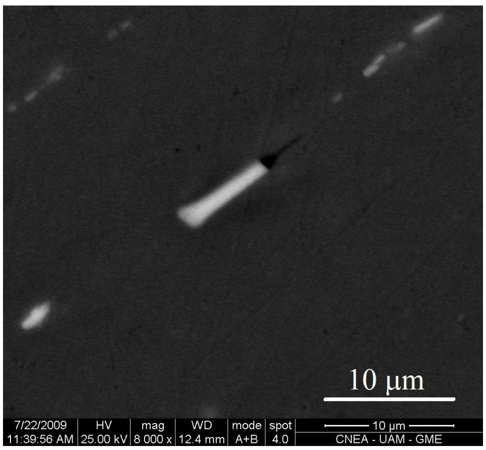

Fig. 5. Morphology of AlFeSi precipitates, stick type

In Figure 6 microcracks and their respective lengths can be seen.

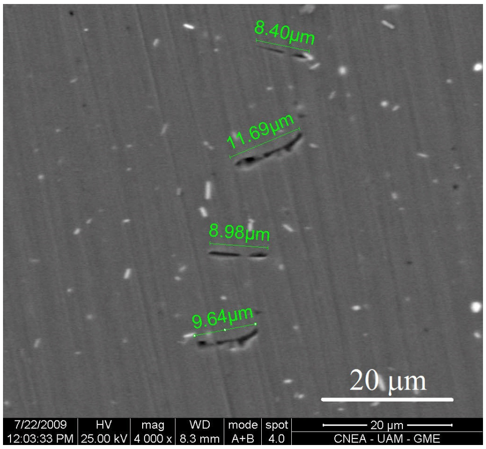

Fig.6.Microcraks

3.2.2. Mechanical strength and electrical resistivity

The results of tensile test and resistivity on samples of wires 2 and 3 mm diameter with two different heat treatments are shown in Table 4.

Table 4: Mechanical strength and electrical conductivity of the alloy 6101M.

Material	Tensile strength [MPa]	Elongation [%]	Electrical conductivity [%IACS]
Wire rod	202	16	50,5%
Wire TT1 Ø 3 mm	351	11	53,4%
Wire TT2 Ø 3 mm	346	11	53,5%
Wire TT1 Ø 2 mm	348	6	52,9%
Wire TT2 Ø 2 mm	335	8	54,2%
Reference AA6101 T65*	300 min.	3 min.	52.5% min.

(*) Aluminium Standards and DATA, published by Aluminium Association Inc.

3.2.3. Torsion test.

Tests on drawn wires were performed with satisfactory results, obtaining values between 40 and 65 twists per meter without breaking.

In the traditional process the values are between 12 and 20 twists per meter [Iraizoz (2005)].

4. Conclusions

From the analysis of the obtained data in the performed tests it is possible to conclude that:

1. The new process improved 14% the tensile strength.
2. The variation of the electrical conductivity has an improvement close to 2.0%.
3. It is evidenced an improvement in the plastic behavior of obtained wires, which is shown in the torsion test, where greater than 40 twists per meter were obtained.

4. Preliminarily the analyzed results show, as a whole, that a 16% improvement in the performance can be achieved for wires obtained by this new method.

5. Based on the foregoing, it is observed that the increase of the mechanical strength of the wires allows improving the design of the electricity transmission lines. As an example, it can be mentioned the possibility of extending the distance between the towers of power transmission reducing their installation costs and the environmental impact.

6. The results of the torsion tests done at the end of the thermo-mechanical processes on the samples, confirm the good integrity through all the steps involved in the manufacture of them. Such integrity is superior to that obtained using only the wiredrawing process.

7. The evaluation of the influence of the new process on productivity and cost of the installation of transmission towers is beyond the scope of this work.

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