EVALUATION OF SILICON VARIATION CONTENT ON MECHANICAL AND ELECTRICAL PROPERTIES OF Al - 0,6 %Mg - [X] %Si

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Abstract. *This paper proposes to evaluate the influence of magnesium variation on mechanical and electrical properties in Al – 0.6 %Mg – [0.4; 0.8 and 1.2] %Si alloys, poured in an unidirectional horizontal mold. The mapping of temperatures in previously chosen points in mold and in the metal along the solidification chamber was realized to determine the solidification curves. By the aid of these curves, was possible to determine the rate of cooling and its speed through obtaining the liquidus temperatures of the studied alloys. After that, the removal of cast body specimen was realized for the tensile test and electrical conductivity. By this way, was established a correlation between the mechanical (tensile strength - TS) and electrical (IACS%) characteristics of the material.*

Keywords*: 6000 alloy; Unidirectional Horizontal Solidification; Electrical Conductivity and Tension Test.*

1. INTRODUCTION

Technology advance and the market competitiveness requires more products with better quality [Fernandes, 2002] boosting the development of the aluminum alloys and, by this way, for these alloys, forming an important function in industry growth [Atxaga, 2001].

The diluted alloys of 6000 series have an intense applicability on wires and cables manufacturing for distribution and transmission of electrical energy on 6101 alloy (Al-Mg-Si) [Fernandes, 2003], by allying good workability with mechanical resistance. An additional advantage by using these alloys is the considerably weight reduction by the low specific mass of aluminum.

This study proposes varying silicon concentrations in an aluminum diluted alloy of 6000 series to verify the results of mechanical and electrical character tests which are necessary to the application in transmission and distribution of electrical energy wires. This applicability requires of material a great trative mechanical resistance and electrical conductivity within the standard specifications to be produced on industrial scale. Integrated in this study we also have thermal characteristics analyzes, withdrawn in the pouring moment of the alloys, for example solidification speed and solidification rate.

2. MATERIALS AND METHODS

As previously mentioned, were utilized alloys of 6xxx series, more precisely alloys of Al-Mg-Si system. The nominal compositions of 6101/6201 alloys are organized in an admissible range, which Si contents change without compromising the identity of the alloys.

To evaluate the influence of silicon variation on mechanical properties of the alloy, the following magnesium contents near to the admissible limits of 6101/6201, [0.4; 0.8; 1.2]% system were adopted. The base alloy adapted to be modified was Al – 0.6 %Mg binary. Chemical composition of the utilized alloys in this work was determined in a mass spectrometer. Results are on Table 1.

The Figure 1 presents a set of useful information for understanding the experimentation. All system is isolated to the heat extraction such occurs only through the metallic block, generating an unidirectional solidification. The temperatures were monitored during the solidification through a set of 6 (six) thermocouples, 4 (four) of “K” type and 2 (two) of “J” type, on specific positions in pouring chamber. The 4 (four) thermocouples “K” type were deposited in the metal on the following positions in metal/mold interface: 7.5 mm; 22.5 mm; 37.5 mm e 52.5 mm and two of “J” type, which one was positioned in mold (metallic mold) and the another one in mold/environment interface. All thermocouples were connected by a coaxial cable to a temperature recorder and the thermal historic of the alloys were passed to a computer, which was realized data treatments.

For reading electrical conductivity was necessary submit the samples to a sequence of cold working: 82 % since ϕ= 9.5 mm diameter for obtaining the diameter ϕ= 3.98 mm. The intensity of cold working that the material was submitted may be evaluated by the aid of Equation 1[Vlack, 1984].

$$\kappa = \left[\frac{A_0 - A_f}{A_0} \right] \text{x } 100 \tag{1}$$

[A_0] e [A_f] are initial and final area of the profile respectively.

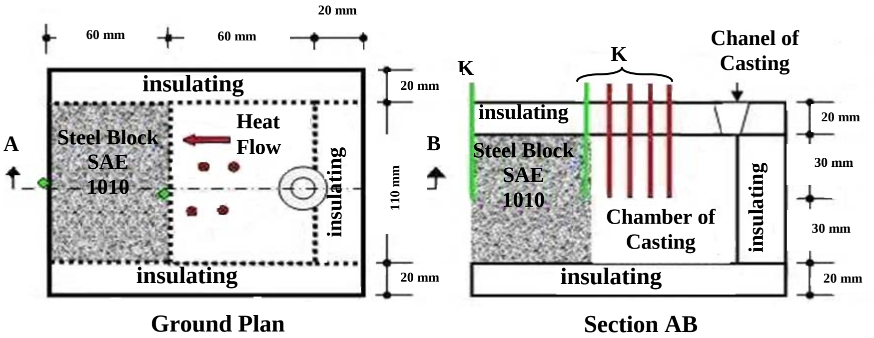

Figure 1. Top and side view of pouring chamber with thermocouples installed in previously chosen positions [Mattos, 2005]

After fusion the alloys were poured with 10% over-heating on solidification device observed on Figure 2. In each assembly was utilized SAE 1010 steel block with thickness of 60 mm, that works as a mold and heat-extractor source from cast metal. Pouring chamber has the following measures 60x60x110 mm.

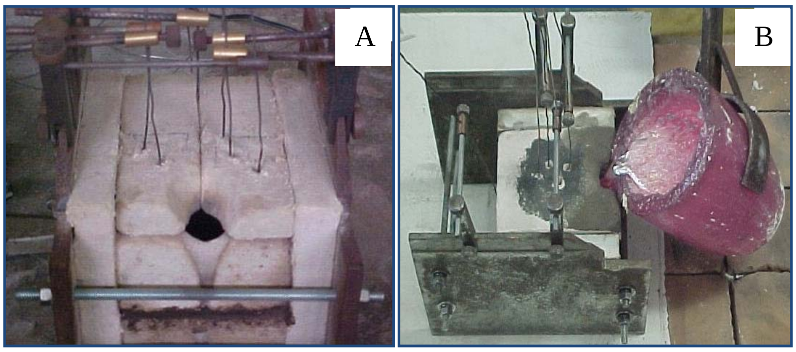

Figure 2. [A] Pouring Chamber and the Thermocouple disposal and [B] Alloy Pouring on Chamber

Test specimens for tensile test were removed from ingot in a transversal position in relation to the heat extraction direction and then machined (figure 3). The transversal collection of test specimens, for tensile test as illustrated on figure 3B, due the necessity to characterize the material through of its more significant crystal structure of the alloys, the Secondary Dendritic Spacing – SDS or λ_2.

The technique utilized for measuring the λ_2 in specific positions of the thermocouples was Schievenbusch's and others [Schievenbusch, 1993] adaption in unidirectional solidification. By this way, this criterion was adapted and the λ_2 value was obtained by the medium distance between dendritic arms, as shown on figure 3 B.

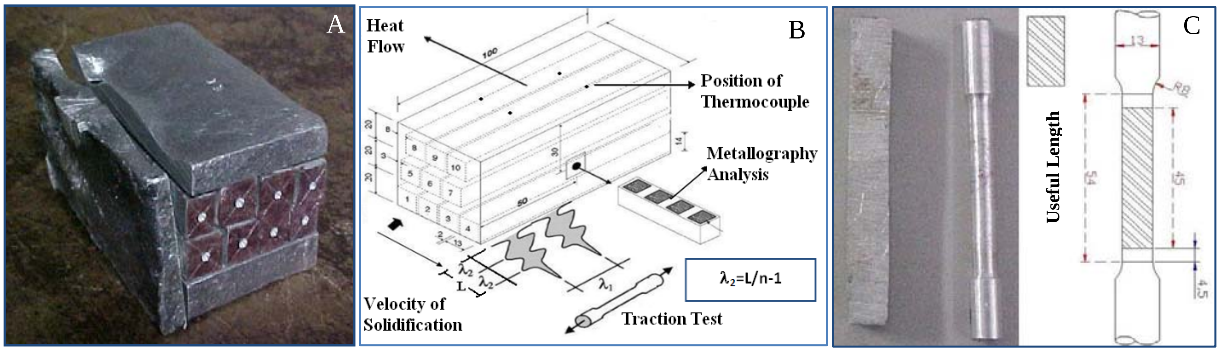

Figure 3. Disposal of the Test Specimens removal: On [A], Photo showing the cut ingot obtained satisfying the previsions on [B], which shows the direction of dendritic evolution in relation to tension specimen collection; On [C], Photo illustrating the bar of square cross section after cutting the ingot and the fabricated test specimen with test specimen dimensions according to ASTM-E8M norm.

Tensile test (KRATOS machine) and electrical conductivity (Micro Ohmeter equipment) was realized for acquisitioning mechanical and electrical properties, figure 4 e, and the following norms NBR 6810 and NBR-6814 were utilized respectively. The test specimen for electrical conductivity test was deformed by rolling and drawing.

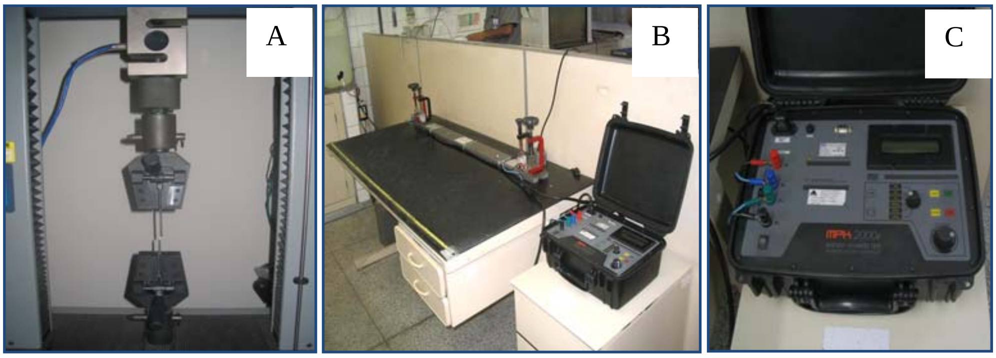

Figure 4. [A] Equipments for Mechanical [KRATOS] and [B;C] Electrical [Micro Ohmeter – Kelvin bridge, MEGABRÁS MPK-2000 model] Characterization

3. RESULTS AND DISCUSSION

The table 1 represents the obtained alloys for the study, each produced alloy generates thermal profiles (figure 6) for being analyzed in each position.

Table 1. Chemical Compositions of the Studied Alloys

Alloys	Si %	Mg %	Fe %	Al	Mg_2Si
Al-0.6%Mg-0.4%Si	0.382	0.617	0.170	98.78	
Al-0.6%Mg-0.8%Si	0.813	0.612	0.154	98.39	
Al-0.6%Mg-1.2%Si	1.22	0.628	0.159	97.86	

On Figure 5A, are related the curves from thermocouples positioned from metal, in previously chosen positions in relation to Metal/Mold (M/M) interface, in mold and in mold/Environment interface illustrating the experimental thermal historic for Al-0.6%Si-0.7%Mg alloy.

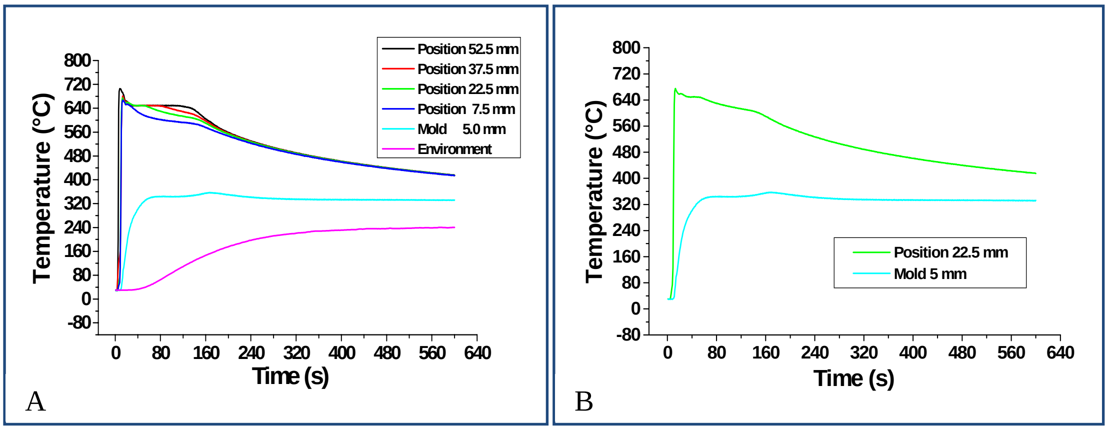

Figure 5. [A] Experimental Thermal Profile obtained of pouring for Al-0.6%Si-0.7%Mg alloy, [B] Thermal Profile of the metal in 22.5 mm position associated to mold profile in 5 mm distance

On Figure 5B is presented thermal profile of the metal of 22.5 mm position associated to mold in a distance of 5 mm as auxiliary for obtaining the pairs [P; t_L].

The objective is obtain the liquidus temperature [T_L], by this way, an horizontal straight line is drawn parallel to abscissa axis [Time] starting by thermal invariance until ordinate axis [Temperature]; then, for determining liquidus time [t_L], starting from thermal profile and thermal invariance was drawn a straight line perpendicular to abscissa axis and, when that axis is crossed, will define the moment when liquidus isotherm reaches each thermocouple.

From the obtained experimental results, the use of a graphic software enables to obtain curves, for example $\mathbf{P=C.t_L^{\,n}}$, as illustrated on Figure 6, which facilitates the construction of experimental equations that relates the displacement speed of liquidus line for Al-0.6%Mg-[0.4; 0.8 e 1.2]%Si alloys in function of position (P) of each thermocouple on Metal/Mold interface, [V_L= f(P)], as illustrated on figure 7 [Quaresma, 1999].

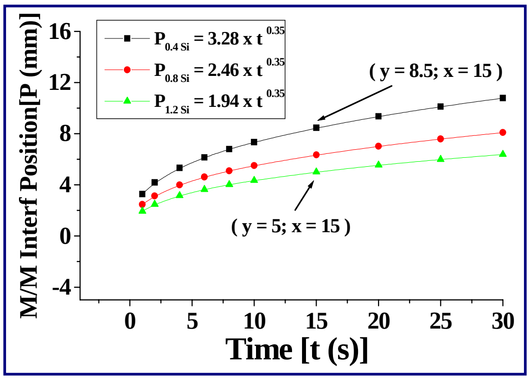

Figure 6. Evolution of Liquidus Isotherm Profiles of the studied alloys, variation on Si content

On graph of figure 7 is evidenced that the curve correspondent to the alloy with 1.2 %Si content shown lower values of V_L demonstrating that the process was sensibly slower when compared to the solidification of another alloys. The same tendency occurs to the rate of cooling, figure 8.

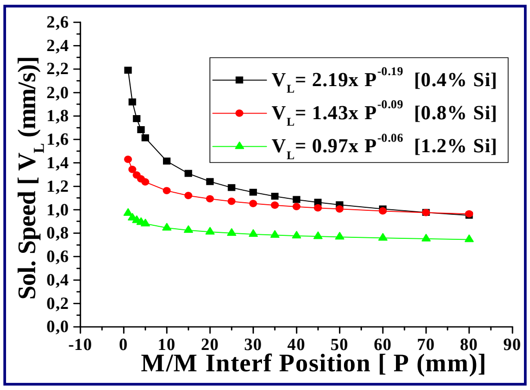

Figure 7. Curves describes the speed variation of liquidus isotherm (V_L) with M/M interface distance in function of Si evolution

Based on results and relating to the parameters: speed of liquidus isotherm **(V_L)** and rate of cooling ($\overset{*}{T}$), exists a correspondence that follows these analytical relation between these two parameters for diluted alloys represented by equation 2 [Garcia, 2001; Quaresma, 1999] as seen on figure 8.

$$\overset{*}{T} = \frac{d_s . L}{k_s} V_L^2 \tag{2}$$

L is Latent Heat of Fusion = 385.000 J/Kg; d_S, Density = 2.550 Kg/m^3; k_S, Thermal Conductivity = 222 W/m.K.

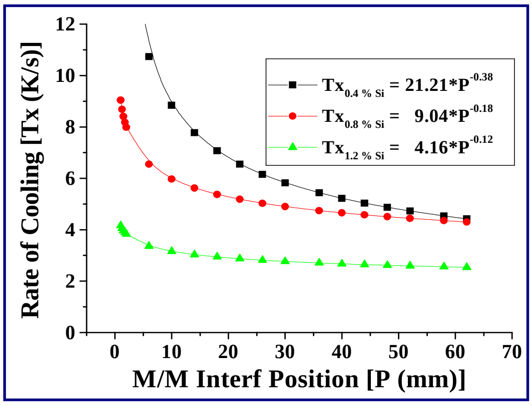

Figure 8. Correlation between Rate of Cooling and Position in relation to M/M Interface and Solute content of the alloys: variation in Si content

All these behavior consequences will provoke different structural arrangements and will reflect directly on physical behavior of the cast.

The increasing easiness in the heat transfer between material and mold has directly consequence on the form of crystal structure produced, as evaluated through the analysis of figure 9 [Garcia, 2001; Quaresma, 1999]

The macrostructure observed on figure 9 is the consequence of the rate of cooling imposed to the system.

On figure 9 is possible to observe that the more Si content the more evident change on form of the crystal structure, since small grains to columnar clearly elongated with evident equiaxial/columnar transition.

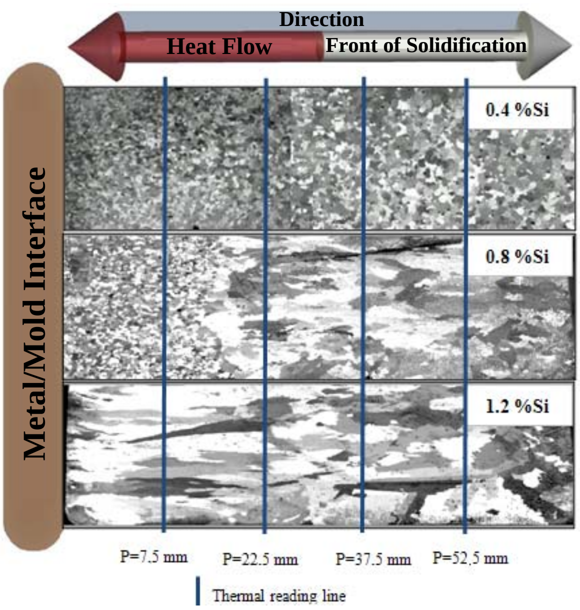

Figure 9. Macrograph of the modified alloys with Si contents proposed

The results of tensile test are on figure 10 in function of the distance of the M/M interface.

The graphs of figure 10 permit to verify that the obtained values on tensile test increase with the silicon concentration on alloy and decrease with an increase on test specimen in relation to M/M interface is higher.

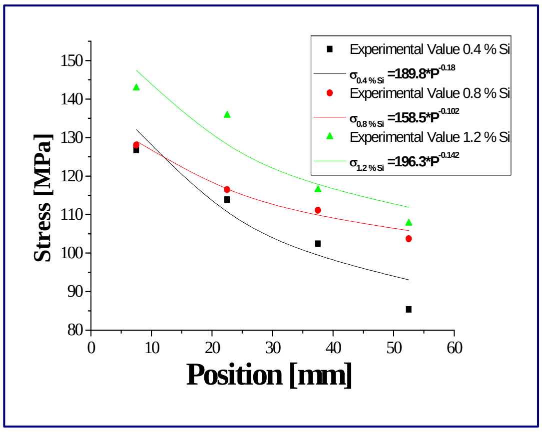

Figure 10. Relation of TS in function of the position

Figure 11 relates the micrographic photos of the alloys with 1.1% Mg on extreme positions with the curves of the secondary dendritic spacing (λ_2 or SDS) in relation to metal/mold interface position.

On figure 11 is observed that the SDS values increase as these are read more distant of M/M interface and as much higher Silicon content on alloy. This is probably related to the reduction of rate of cooling of the metal. As the solidified layer gets thicker, advance of solid/liquid interface gets slower, increasing gradually the thermal resistance. This set of behavior can support the phenomenon of macro segregation (normal segregation).

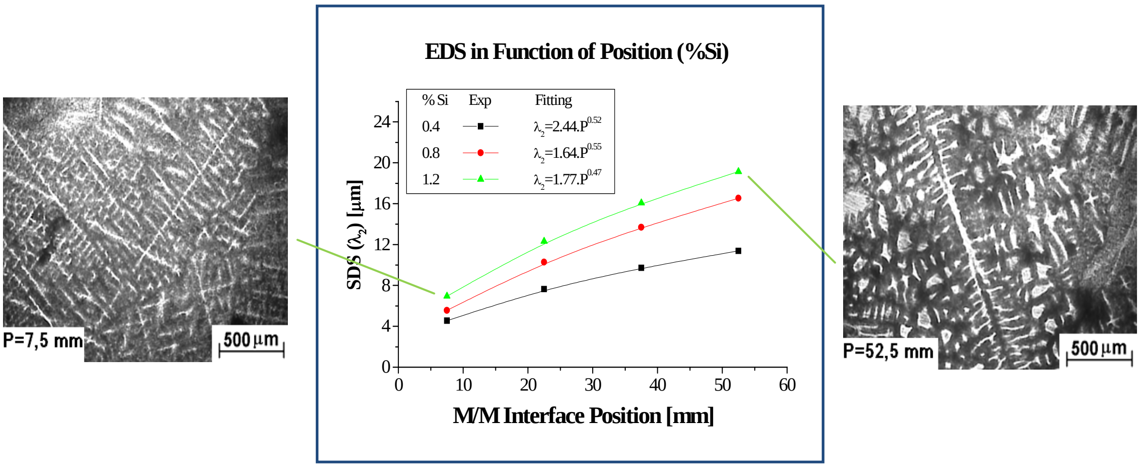

Figure 11. SDS in function of position and micrographic photo

The results of electrical conductivity of the studied alloys are in function of the M/M position the wire 3.98 mm diameter (figure 12), which was submitted to cold-rolling forming process.
In results of electrical conductivity (figure 12) of Al-0.6%Mg -(0.4 %; 0.8 %; 1.2 %) Si alloys, is observed that with the addition of solute, presented lower values of conductivity and increase on distance in relation to M/M interface, for Al – 0.6 Mg – [0.4; 0.8] %Si alloys, as much as electrical conductivity.

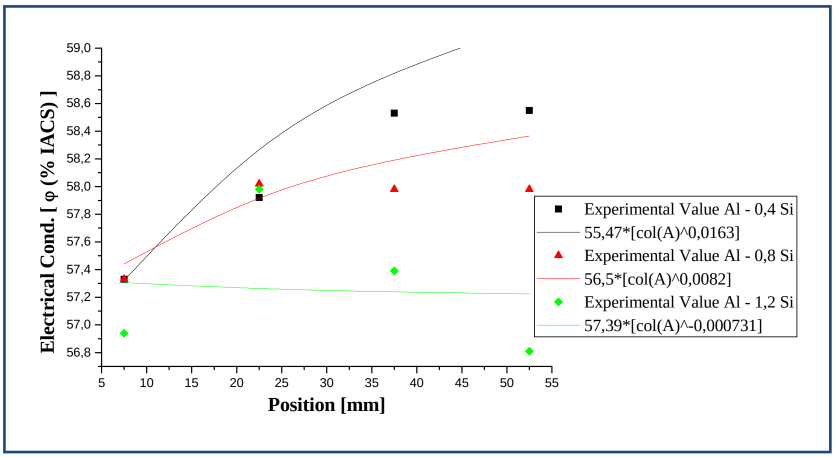

Figure 12. Electrical conductivity in relation of the position the wire 3.98 mm diameter

4. CONCLUSION

As consequence of affinity between metal and mold is observed:

The higher solute content (1.2 %Si) present lower values of Speed and Rate of Cooling that reflect directly on formation of final structure of casted; presenting higher SDS values with crescent content of Si and each more distant of metal/mold interface.

These two aspects are found reflected on obtained values of Stress that decrease.

As consequence of deformation grade applied is observed:

The higher tangle of the discordances due to crescent solute content and cold-work impost on samples, appears to difficult the passage of the electrons and consequently these ones present lower electrical conductivity values (IACS%).

5. REFERENCES

ASTM – “Standard Test Methods for Tension Testing of Metallic Materials” *[METRIC] (Designation: E 8m – 00B – METRIC);*

Atxaga G., Pelayo A.,and Mrisan A., “Effect of Microstruture on Fatigue Behaviour of Cast Al-7Si-Mg Alloy”; vol 17, Materiai Science and Technology; 2001;

Fernandes Neto, M.; Pires, J. C. S.; Garcia, A.; Pinto, F. N.; “Investigação de inclusões não metálicas em fios elétricos de alumínio”; REM – Revista Escola de Minas, Brasil, v.55, n.2; p. 97-101, 2002;

Fernandes, Denílson Santos; Sena, Hélido Cleidson de Oliveira; Kishi, André Oliveira; Sá, Fernando Antônio; Quaresma, J. M. do Vale; “Avaliação do Comportamento do Mg na Liga Al-Mg-Si (6101) Dentro de uma Faixa Admissível para a Fabricação de Fios e cabos Elétricos”; 58º Congresso Internacional anual da ABM - RJ, 2003;

Garcia, A.; “Solidificação: Fundamentos e Aplicações”, Editora da UNICAMP, Campinas, Brasil, 2001;

Mattos, P.R.O.; “Estudo da Trabalhabilidade da Liga Al-0,5%Si-0,6%Cu, Modificada com Diferentes Teores de Magnésio”, 112 f. Dissertação (Mestrado em Engenharia Mecânica) - Universidade Federal do Pará, *Orientador:* José Maria do Vale Quaresma, 2005;

NBR 6810 – “Fios e cabos elétricos tração à ruptura em componentes metálicos” – Especificação. São Paulo, 1981;

NBR 6814/1985 – “Ensaio de resistência elétrica”. Especificação. São Paulo,1985;

Quaresma, J. M. V.; “Correlação entre Condições de Solidificação”, Microestrutura e Resistência Mecânica – Tese de Doutoramento - UNICAMP – FEM; 1999;

Schievenbusch, A.; Zimmermann, G.; Mathes, M.: “Comparison of different analysis techniques to determine the cellular and dendritic spacing Materials Science and Engineering”, A, 173 (1), pp.85-88, 1993;

Vlack, V.; Hall, L., “*Princípios* de Ciência e Tecnologia dos Materiais”, tradução Edson Monteiro, editora Elsevier, 21° Reimpressão, Rio de Janeiro, 1984;

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