SPEED OF SOLIDIFICATION [V_L] AND MAGNESIUM CONTENT INFLUENCE IN Al-Mg-Si ALLOYS UNIDIRECTIONALLY SOLIDIFIED

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Abstract. *This paper aims to establish experimental relations between the solidification thermal variables speed of solidification [V_L], cooling rate [$\dot{T}$] and Mg contents in 6000 series aluminum alloys, starting with the modification of binary Al-0.6%Si with Mg contents, utilizing thermal records of the castings in molds, which made possible the unidirectional heat extraction. The cast alloys produced in the laboratory were melted in a muffle furnace with a 10% overheating and poured by a graphite crucible. The experimental velocity curves obtained express a lower initial profile with increasing Mg content. On the structural evolution, the columnar/equiaxed transition occurred on the same cooling rate of 0.85 K/s. These results point to the possibility of inhibition of the intense convective movement by the lower speed of solidification and by the fostering of the growing columnar grains by the lower cooling rate. Analyzing the results, it was found that the speed of solidification and cooling rate decreased with the Mg content variation, this variables show converging values from the middle point of the ingot, coinciding with the region of structural transition.*

Keywords*: 6101 alloy, 6201 alloy, Speed of Solidification, Diluted alloys.*

1. INTRODUCTION

Aluminum alloys are materials with extensive use in various applications due to some characteristics as its electrical and thermal conductivity, good tensile strength and conformability. Alloying additions such as copper, magnesium and silicon are some of the most used.

Approximately 90% of the worldwide alloy production passes through a solidification stage, which demands a set of operational conditions for the manufacturing materials with specific characteristics by structural and chemical variations, which, even nowadays are studied. Interdendritic spacings and grain size are structural parameters that are influenced by the metal/mold system thermal behavior at me solidification process, imposing, consequently, a narrow correlation between this one and the resulting microstructure.

Solidification is processed by the occurrence of a solid nuclei with random crystallographic orientations in the liquid, which grow with plane, cellular or dendritic morphology and constitute at the end of the process, the crystalline grains. On crystalline materials, in general, three well defined distinct zones can be identified: chilled, columnar and equiaxed grains.

Macrostructure characterizes itself by the appearing of structural zones according with the conditions of some parameters in which solidification occurs. As thermal parameters are the dislocation speeds of the liquidus isotherm or speed of solidification (V_L), thermal gradients (G_L) and local cooling rate (T_L). As operational parameters, there are the pouring temperature (T_V), mold material, chamber dimensions, metal/mold and mold/environment interface heat transfer coefficients (h_i) and (h_{amb}). These parameters are always straightly correlated, influencing the structural formation of the material, what is reflected on mechanical properties. As we note this correlation, it is possible to establish mechanisms that allow forecasting the mechanical properties of the material, as a function of the solidification conditions.

6101 and 6201 alloys are the most used of the 6xxx series, on wire and cable manufacturing for primary transmission and distribution lines, specially because of its good balance between tensile strength and electrical conductivity (approximately 57% IACS (International Annealed Copper Standard) after heat treatment. This is the reason why the use of Al-Mg-Si has conquered space on the wire and cable industry over the traditional Aluminum Conductors Steel Reinforced (ACSR).

In order to improve productivity through a correlation between mechanical properties of Al-Mg-Si alloys with thermal parameters acting on solidification, it was analyzed the influence of Mg content variation on the experimental relation of the liquidus isotherm (V_L) in established positions on the metal, starting off the metal/mold interface in unidirectional solidification conditions, and comparing this variation with the resulting macrostructure.

2. MATERIALS AND METHODS

In the present study, the 6xxx series alloys were used (6101/6201), the chemical compositions of the materials are in a permissible interval, in which Mg and Si content vary without compromising the alloys identity. With the objective of evaluate the influence of magnesium content variation, next to the permissible limits of the 6101/6201 system, on mechanical properties of the ternary Al-Mg-Si, it was adopted a variation criterion, in which the Si content is fixed in 0,6%, and the Mg content varied in 0,5%; 0,7% e 1,1 %. Chemical compositions of the studied alloys were determined on a mass spectrometer and are presented on table 1.

Table 1. Alloys chemical composition

Alloy	Si%	Mg%	Fe%	Al%	Others%
Al-0,6%Si-0,5%Mg	0,6574	0,5388	0,1813	98,5896	0,0329
Al-0,6%Si-0,7%Mg	0,6184	0,7631	0,1746	98,4259	0,0180
Al-0,6%Si-1,1%Mg	0,6480	1,1326	0,1932	97,9939	0,0255

Alloys were placed in graphite crucibles and casted in a muffle furnace. For each alloy it was adopted a 10% overheating over its liquidus temperature. After fusion, the alloys were casted in a solidification apparatus, in which its assemblage utilized a steel SAE 1010 block with 63 mm of wall thickness that worked as a mold and heat extracting source of the melt. The internal space of the casting chamber presented the following dimensions: 60x60x110 mm.

The whole system is insulated in such a way that the heat extraction happens only through the metallic mold, generating, this way, a unidirectional solidification. The temperatures were monitored during solidification, through a group of 6 (six) thermocouples, being 4 (four) of the “K” type and 2 (two) of the “J” type, in specific positions on the casting chamber, the “K” type thermocouples were placed on the metal, on the following positions in relation to the metal/mold interface: 7,5mm; 22,5mm; 37,5mm e 52,5mm, and with the two of the “J” type, one was positioned on the mold (metallic block) and another at the mold/environment interface. Figure 1 shows the casting chamber. All the thermocouples were connected by a coaxial wire to a temperature register and the captured thermal historic of the alloys was later fed on a computer.

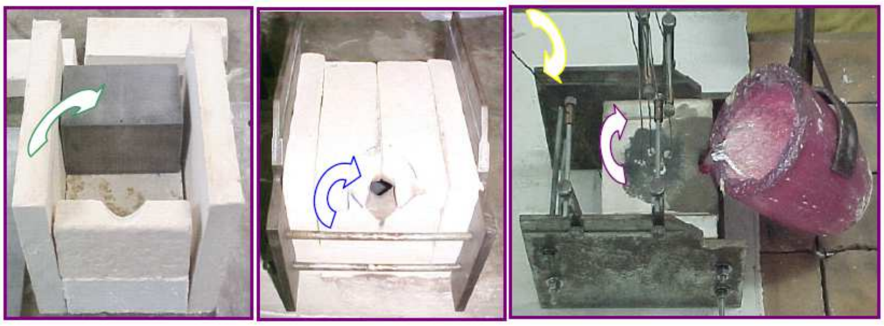

Figure 1. Casting chamber: (a) Partially mounted, (b) mounted and (c)the record of the moment of pouring.

From the obtained experimental data, the utilization of a graphic software allowed the obtaining of type $\mathbf{P=C.\ t_L^n}$ curves, which makes possible the construction of experimental equations that establish the relations between the dislocation speed of the liquidus line as a functions of the position (P) of each thermocouple in relation to the metal/mold interface [VL= f(P)] (Quaresma, 2000), as shown in figure 5.

3. RESULTS AND DISCUSSION

Recent studies about viscosity/fluidity (Verran, 2004) suggest that Aluminum alloys with Silicon and Magnesium content present greater fluidity, as the content of this elements increases, inside certain limits, on the alloy. Other study about this feature (Kim and Loper, 1999) analyzed the fluidity of Al-Si alloys, in which the small solidification intervals result in a nonuniform metal/mold adherence, causing thicker metal layers that contracts itself, turning the own metal to a cooling agent in the alloy.

From the analysis of data contained in figure 2a, taking as a reference the time of 15 seconds, it is evident that the liquidus line, in the 1,1%Mg alloy, travels a significantly inferior distance than the one travelled by the 0,5%Mg alloy, besides starting from a inferior position in relation to the two other alloys. On the other hand, the curves contained on figure 2b, also make evident that the alloy with greater Mg content presents lower speed profile.

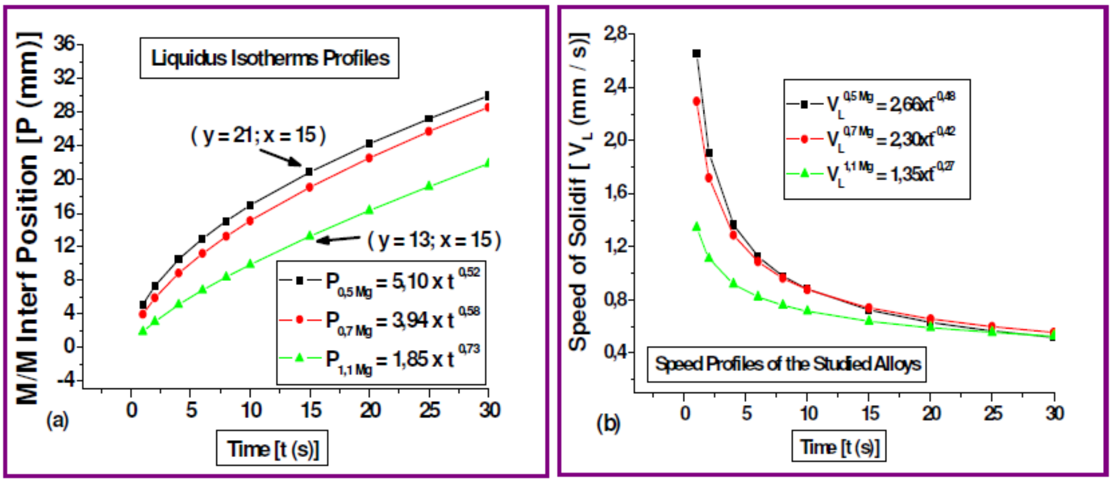

Figure 2. Liquidus Isotherms and Speed Profiles

The easy heat transfer between the metal and the mold has direct consequence over the solidification thermal variables, as can be evaluated through the analysis of figure 3, as well of the equations of cooling rate (Eq.1), solidification time (Eq.2), speed of solidification (Eq.3) and cooling rate dependent of the interfacial coefficient (Eq.4). (Quaresma, 2001), (Garcia, 2001):

$$\dot{T} = \frac{d_s L}{k_s} V_L^2 \quad (1)$$

Where L, Latent Heat of Fusion = 385.000 J/Kg; d_S, Density = 2.550 Kg/m^3; kS, Thermal Conductivity = 222 W/m.K (Quaresma, 1999).

$$t = \frac{1}{4a_s\phi^2} S^2 + \frac{Ld_s}{h_i\left[T_f - T_0\right]} S \quad (2)$$

However, the differentiation of equation 2 (Eq.2) allows us to obtain the equation of Speed of Solidification [V_L] in the form of equation 3 (Eq.3):Where L, Latent Heat of Fusion = 385.000 J/Kg; d_S, Density = 2.550 Kg/m^3; k_S, Thermal Conductivity = 222 W/m.K (Quaresma, 1999).

$$V_L = \frac{ds}{dt} = \left(\frac{1}{2a_s\phi} S + \frac{Lds}{\left(T_{f-}T_0\right)h_i} \right)^{-1} \quad (3)$$

Which, substituted in Eq.1, allows to write it in the form below and shows the dependence of operating parameters, like the cooling rate and dislocation velocity of the liquidus isotherm [V_L], of the physical parameters, of each material, on solidification evolution.

$$\dot{T} = \frac{Ld_s}{k_s} \left(\frac{1}{2a_s\phi^2} S + \frac{Lds}{\left(T_{f-}T_0\right)h_i} \right)^{-2} \quad (4)$$

Equation 4 (Eq.4) indicates that solidification, on the initial moments, almost exclusively depends on the metal/mold interface heat transfer coefficients [hi].

The group of results related on figure 3 allows the evaluation of the interconnection of the experimental speed values and the cooling rates, obtained when Eq.1 is used. On figure 3a, it is observed that the V_L values tend to converge from the position 26 mm and on figure 3b, and this convergence can be observed on the 36 mm position.

These results, point to the possibility of inhibition of the intense convective movement by the lower V_L and by the fostering of the growing of columnar grains by the lower cooling rate, as long as Mg content increases.

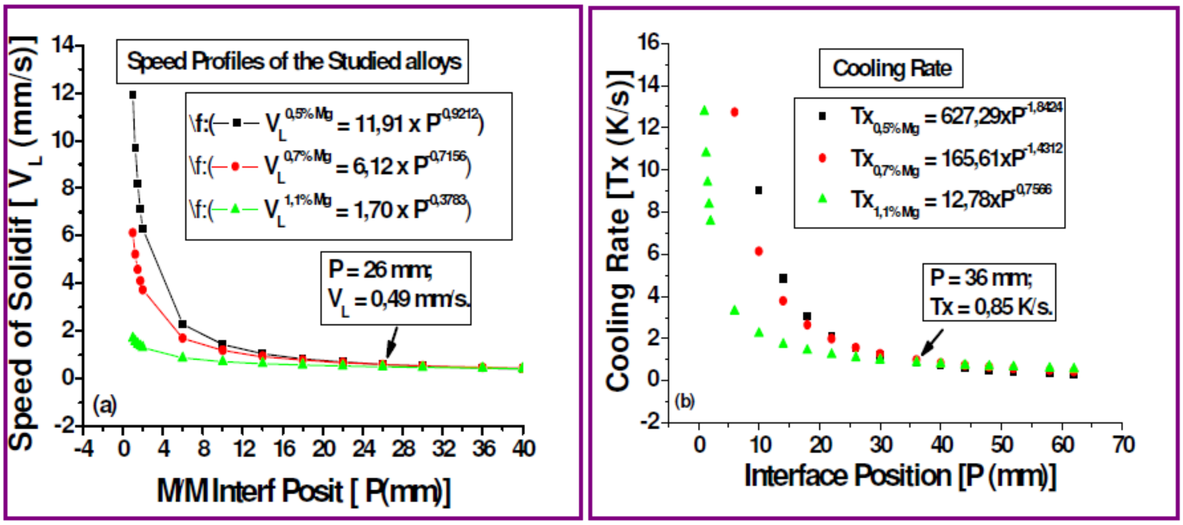

Figure 3. (a) compares the V_L profiles, (b) compares the evolution of the heat transfer rates for the Al-0,6%Si-[0,5.0,7 and 1,1]%Mg alloys, respectively.

4. CONCLUSION

Speed of Solidification decreased with the increasing of Mg contents on the alloy, as the same way cooling rate. These results are in accordance with the findings of Rodigues (2007), the author describes that this is due to the increasing solidified layer that imposes greater resistance to the heat flux. These variables present, in each case, converging values from the middle of the ingot, coinciding with the region of structural transition. Peres (2005) also found these results with increasing solute content on an Al-Si alloy. The author also explains that exists a compensation between the thermal parameters of the hypoeutectic alloys, this conduces to a unique behavior and common experimental laws are observed for cooling rate and speed of solidification. At the studied levels, Mg content show a tendency on stabilizing the columnar structure near the mold walls, suggesting the use of powerful grain refiners. Rodrigures (2007) Also shows us this evidence, and adding that the ingot macrostructures are affected by Mg content, indicating that the columnar/equiaxed transition converged to values near the mold walls.

This growing association of Si and Mg contents with fluidity, when improved mechanical performance [workability] is desired, must be severely observed, because increasing fluidity by provoking better mold wettability by the metal, has, as a consequence, the formation of air gaps between the metal and the molds , each time smaller and associated with the formation of coarse grains, by the decreasing of the cooling rate and low Speed of Solidification, that may endanger the desirable performance.

5. ACKNOWLEDGEMENTS

The authors would like to thank the financial support and donation of materials from ELETRONORTE and ALUBAR METAIS E CABOS S.A.

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7. RESPONSIBILITY NOTE

The authors, Johnyson Feitosa, Pedro Lamarão, Washington Luis and José Quaresma are the only responsible for the printed material included in this paper.