Solidification thermal parameters and dendritic growth during the horizontal directional solidification of Al-7wt.%Si alloy

Parâmetros térmicos e crescimento dendrítico durante a solidificação direcional horizontal da liga Al-7%Si

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Abstract

The main purpose of this work is to investigate the influence of thermal parameters such as growth rate (V_L) and cooling rate (T_R) on the primary dendrite arm spacings (λ_1) during the horizontal transient directional solidification of Al-7wt.%Si hypoeutectic alloy. The primary dendrite spacings were measured along the length of the samples and correlated with these thermal parameters. The variation of dendrite spacings is expressed as a power law function of V_L and T_R given by the formulas $\lambda_1 = 55(V_L)^{-1.1}$ and $\lambda 1 = 212\ (T_R)^{-0.55}$, respectively. A comparative study between the results of this work and those from the literature proposed to investigate these dendrite spacings during the upward and downward vertical directional solidification of Al-7wt.%Si alloy is also conducted. Finally, the experimental data are compared with some predictive dendritic models from the literature.

Keywords: Directional solidification, unsteady state, primary dendrite arm spacings, Al-Si alloys.

Resumo

O principal objetivo desse trabalho é investigar a influência dos parâmetros térmicos velocidade de solidificação (V_L) e taxa de resfriamento (T_R), nos espaçamentos dendríticos primários (λ_1) da liga hipoeutética Al-7%Si, durante a solidificação direcional horizontal, em regime transiente. Os valores de λ_1 foram medidos ao longo do comprimento do lingote e correlacionados com esses parâmetros. A variação dos espaçamentos dendríticos estudados é expressa por meio de funções na forma de potência de V_L e T_R dadas, respectivamente, por $\lambda_1 = 55(V_L)^{-1.1}$ e $\lambda_1 = 212\ (T_R)^{-0.55}$. Um estudo comparativo é realizado entre os resultados encontrados nesse trabalho e aqueles obtidos para a mesma liga quando solidificada direcionalmente nos sistemas verticais ascendente e descendente, sob as mesmas condições assumidas. Finalmente, os resultados experimentais obtidos são comparados com valores fornecidos por alguns modelos teóricos propostos na literatura para analisar espaçamentos dendríticos primários.

Palavras-chave: *solidificação direcional, regime transitório, espaçamentos dendríticos primários, ligas Al-Si.*

1. Introduction

Aluminum alloys with silicon as a major alloying element consist of a class of alloys which provides the most significant part of all the shaped castings manufactured. This is mainly due to the outstanding effect of silicon in the improvement of casting characteristics, combined with other physical properties such as mechanical properties and corrosion resistance. In general, an optimum range of silicon content can be assigned to casting processes. For slow cooling rate processes (sand, plaster, investment) the range is 5–7 wt.%, for permanent molds 7–9 wt.% and for die castings 8–12 wt.% (Peres *et al*., 2004).

A number of directional solidification studies characterizing primary (λ_1) and secondary (λ_2) dendrite arm spacings as a function of alloy concentration (C_0), tip growth rate (V_L) and temperature gradient ahead of the macroscopic solidification front (G_L) can be found in literature (Gunduz and Çadirli, 2002; Rocha *et al*., 2003A; Carvalho *et al*., 2013; Nogueira *et al*., 2012). Bouchard and Kirkaldy (1997) and Garcia (2007) have summarized these studies and grouped them into two categories: those involving steady state heat flow solidification and those in unsteady state regime. In the former category, solidification is controlled and the significant controllable variables, G_L and V_L are kept constant and are independent of each other. In the latter group which characterizes, for instance, the solidification conditions of a body of irregular shape, these variables are interdependent and vary freely with time. The analysis of dendritic structures in the unsteady state regime is very important, since it encompasses the majority of industrial solidification processes. Investigations on the primary and secondary dendritic growth of binary alloy systems during transient solidification are reported in literature: Sn-Pb (Rocha *et al*, 2003A; Rocha *et al*, 2003B), Al-Cu (Gunduz and Çadirli, 2002; Rocha *et al*., 2003A), Al-Si (Peres, *et al*., 2004; Carvalho *et al*., 2013), Pb-Sn (Li *et al*., 1999) e Mg-Al (Zhang *et al*., 2007).

Among the theoretical models existing in literature, only those proposed by Hunt and Lu (1966) for primary spacings and Bouchard and Kirkaldy (1997) for primary and secondary spacings assume solidification in unsteady state heat flow conditions.

In the work developed by Peres et al. (2004) under unsteady state upward vertical directional solidification conditions, primary arm spacings were observed to decrease as the tip cooling rate or the tip growth rate increased for a given Al–Si alloy composition. The authors have used silicon contents of 3%, 5%, 7% and 9% and the primary spacings were found to be independent of composition. The dendritic primary spacing experimental scatter is included inside the range of minimum and maximum λ_1 values predicted by Hunt–Lu's model and Bouchard–Kirkaldy's model predictions are generally slightly above the experimental points. The experimental variation of primary dendrite spacings for all compositions analyzed by Peres et al (2004), is expressed as a power law function of T_R given by the formula $\lambda_1 = 220(T_R)^{-0.55}$. Carvalho *et al.* (2013) have conducted a study with the Al-3wt.% Si alloy considering the same solidification conditions assumed by Peres et al.(2004). Primary dendrite arm spacings were observed to decrease as the tip growth rate or the tip cooling rate increased. A power law function characterizes the experimental variation of primary spacings with tip growth rate with an index of –1.1 as well as a –0.55 power law characterizes the experimental variation of primary spacings with cooling rate

The gravity effects in relation to the dendritic growth have been investigated with the chill placed in general on the bottom or top of the mold. In the case of vertical upward directional solidification, the influence of the convection is minimized when solute is rejected for the interdendritic regions, providing the formation of an interdendritic liquid denser than the global volume of liquid metal. When the process is carried out vertically downward, the system provides the melt convection which arises during the process. In the horizontal directional solidification, when the chill is placed on the side of the mold, the convection in function of the composition gradients in the liquid always occurs. An interesting feature of the horizontal configuration is the gradient of solute concentration and density in vertical direction because solute-rich liquid falls down whereas free solvent-crystals rise due to the buoyancy force. Moreover, there will also be a vertical temperature gradient in the sample as soon as a thermosolutal convection roll emerges. In spite of these particular physical characteristics, only a few studies (Nogueira *et al*., 2012) have reported these important effects of melt convection and direction of growth on dendrite arm spacings for this particular case. The main purpose of this work is to investigate the influence of thermal parameters such as growth rate (V_L) and cooling rate (T_R) on the primary dendrite arm spacings (λ_1) during the horizontal transient directional solidification of Al-7wt.%Si hypoeutectic alloy. A comparative study between the results of this work and those from the literature proposed to investigate these dendrite spacings during the upward and downward vertical directional solidification of Al-7wt.%Si alloy is also conducted. Finally, the experimental data are compared with some predictive dendritic models from the literature.

2. Experimental procedure

Experiments were carried out with an Al-7wt.%Si hypoeutectic alloy. The chemical compositions of metals that were used to prepare the alloy investigated and the corresponding thermophysical properties are those reported by Peres (2004). The casting assembly used in solidification experiments has been detailed in previous articles (Nogueira *et al*., 2012; Carvalho *et al*., 2013). It was designed in such a way that the heat was extracted only through a water-cooled system placed in the lateral mold wall, promoting horizontal directional solidification. The carbon steel mold used had a wall thickness of 3 mm, a length of 110 mm, a height of 60 mm and a width of 80 mm. The lateral inner mold surfaces were covered with a layer of insulating alumina and the upper part of the mold was closed with refractory material to prevent heat losses. In order to ensure reproducibility of results some features of the experimental setup were standardized such as thermal contact condition at the metal-mold interface corresponding to the stainless steel heat-extracting surface being polished cooled, starting melt superheat in 10% above the liquidus temperature (T_L) and water flow constant of 12 LPM. The experimental procedure was as follows: the alloy was melted in situ using an electrical furnace whose heaters had their power controlled in order to permit a desired superheat to be achieved. Approaching the superheat temperature, the mold was taken from the heater and set immediately on a water cooled carbon steel chill. Water was circulated through this cooling jacket keeping the carbon steel plate during the solidification at a constant temperature of about 25^{0}C and thus inducing a longitudinal heat transfer from the mold. Solidification occurred dendritically from the lateral chill surface forming a columnar structure. During the solidification process, temperatures at different positions in the alloy samples were measured and the data were acquired automatically. For the measurements, a set of five fine type K thermocouples was used. The thermocouples were sheathed in 1.6 mm diameter steel tubes, and positioned at 5, 10, 15, 30, and 50 mm from the heat-extracting surface. The thermocouples were calibrated at the melting point of Al exhibiting fluctuations of about 0.4^{0}C and 1^{0}C respectively, and connected by coaxial cables to a data logger interfaced with a computer.

Selected transverse (perpendicular to the growth direction) sections of the directionally solidified specimens at 5, 10, 15, 20, 30, 40, 50 and 60 mm from the metal-mold interface were polished and etched with a solution of 0.5%HF in water for micrograph examination. Image processing system Olympus BX51 and Image Tool (IT) software were used to measure primary dendrite arm spacings (about 20 independent readings for each selected position, with the average taken to be the local spacing) and their distribution range. The method used for measuring the primary arm spacing on the transverse section was the triangle method (Gunduz and Çadirli, 2002; Rocha *et al*., 2003A).

3. Results and discussion

Experimental cooling curves for the five thermocouples inserted into the casting during solidification of the alloy investigated in this study are shown in Figure 1(a) in which T_P is the initial melt temperature. It is well known that the primary dendritic arm spacings are dependent on solidification thermal variables such as V_L and T_R all of which vary with time and position during solidification. In order to determine more accurate values of these parameters, the results of experimental thermal analysis have been used to determine the displacement of the liquidus isotherm, i.e., the thermocouples readings have also been used to generate a plot of position from the metal-mold interface as a function of time corresponding to the liquidus front passing by each thermocouple. A curve fitting technique on such experimental points has generated power functions of position as a function of time. Experimental positions of liquidus isotherm as a function of time are shown in Figure 1(b). The derivative of this function with respect to time has yielded values for V_L. The T_R profile was calculated by considering the thermal data recorded immediately after the passing of the liquidus front by each thermocouple. The method used for measuring the tip cooling rate was used by Rocha (2003A). Figures 1(c) and 1(d) show, respectively, these results.

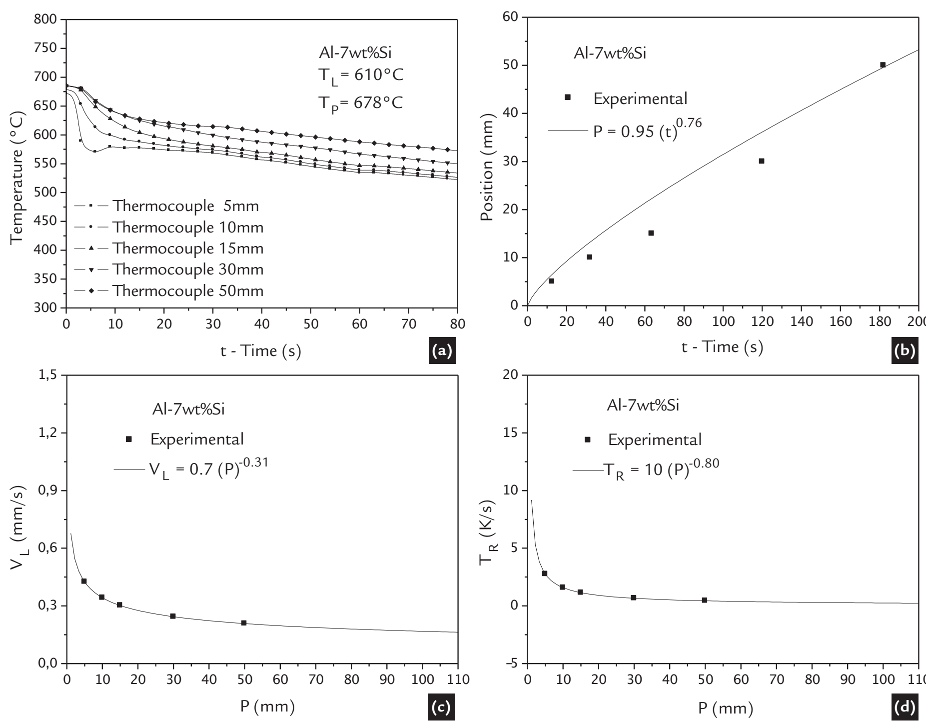

Figure 1
(a) Experimental cooling curves for five thermocouples;
(b) Experimental position of liquidus isotherm as function of time;
(c) Tip growth rate as function of position;
(d) Tip cooling rate as function of position.

Figure 2 presents microstructures of cross section of samples at 10, 30, and 60 mm from metal-mold interface, showing the primary dendrite arms. The dendrite arm spacings were sufficiently distinct to make reasonably accurate measurements along the casting length.

Figure 3(a) shows the average experimental values of primary dendritic spacings as a function of distance from the metal-mold interface obtained in this work. It is observed that these dendrite arm spacings increase with the distance from the heat-extracting surface. In order to correlate the primary dendrite arm spacings measured from the afore-mentioned microstructures with solidification thermal variables, they are plotted as a function of V_L and T_R in Figures 3(b) and 3(c). The average dendritic spacings along with the standard variation are presented in these figures, with the lines representing an experimental power function fit with the experimental points. It is observed that the use of a water-cooled mold imposes higher values of tip growth rates and cooling rates near the casting surface and a decreasing profile along the casting due to the increasing thermal resistance of the solidified shell with distance from the cooled surface. This influence translates to the observed experimental values of primary dendritic spacings. As shown in Figures 3(b) and 3(c), the primary dendrite arm spacings were found to decrease as the V_L is increased. Most of the results from the literature pertaining to λ_1 in binary Al-Cu (Rocha *et al*, 2003A and 2003B) and Al-Si (Peres *et al*., 2004; Carvalho *et al*., 2013) alloys also indicate a decrease in these spacings with decreasing V_L. Furthermore, a power law function characterizes the experimental variation of primary spacings with tip growth rate with an index of –1.1, i.e., $\lambda_1 \propto (V_L)^{-1.1}$. It can be observed in Figure 3(c) that a –0.55 power law characterizes the experimental variation of primary spacings with the cooling rate. This is in agreement with observations reported by Rocha *et al* (2003A), Peres *et al* (2004) and Carvalho *et al* (2013) that exponential relationships λ_1 = constant $(\dot{T}_R)^{-0.55}$ best generate the experimental variation of primary dendritic arms with the cooling rate along the unsteady state solidification of Al–Cu and Al–Si alloys, respectively.

Figure 3(d) shows the comparisons between the present experimental results of primary spacings with theoretical predictions furnished by unsteady-state predictive models: Hunt–Lu's model (1966) and Bouchard–Kirkaldy's model (1997), with a calibration factor a_1 = 250 for Al–Si alloys, as suggested by these authors. It can be seen that there is a good approximation between the experimental results and those calculated by Bouchard-Kirkaldy's model. On the other hand, the experimental values are close to the upper limit of Hunt–Lu's model. The predicted dendritic spacings calculated for unsteady solidification by Hunt-Lu's and Bouchard- Kirkaldy's models are subjected to deviations caused mainly by the unaccounted diffusion relaxations and coring reductions for primary spacings. Other uncertainties such as thermophysical properties can also affect the calculated results. Furthermore, the assumption that the partition coefficients and the liquidus slope are constant throughout the entire solidification range is quite inaccurate for some binary systems.

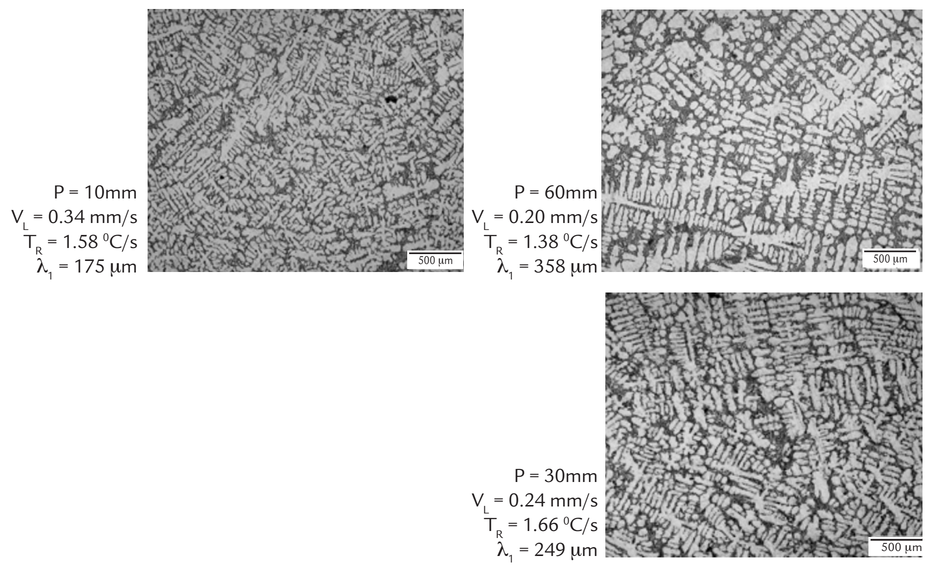

Figure 2
Micrographs of Al-7wt.%Si alloy cross section showing the variation in primary interdendric spacings with the distance from the cooled stainless steel chill.

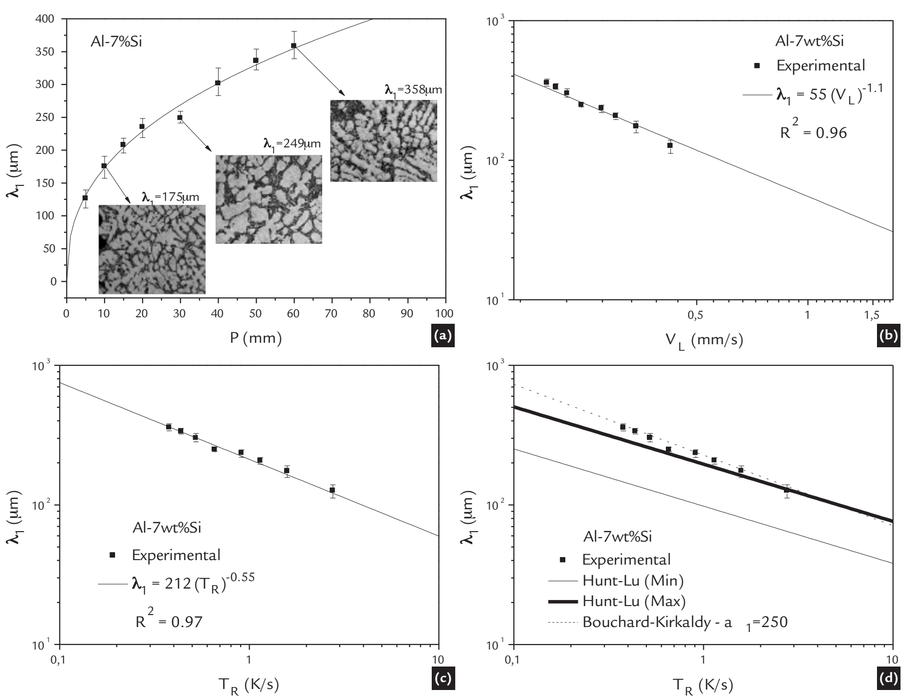

Figure 3
Primary dendrite arm spacing for the Al-7wt.%Si as function of:
(c) tip cooling rate and
(d) comparison of experimental and theoretical primary dendrite arm spacings as function of cooling rate.

Table 1 summarizes the results of the present experimental investigation and those obtained by Peres *et al*. (2004) and Spinelli *et al*. (2005) concerning values of primary dendrite spacings as function of cooling rate during upward, downward, and horizontal directional solidification of Al-7wt.%Si alloy. It can be seen that the same −0.55 power law characterizes the experimental variation of these spacings with cooling rate in systems with different configurations.

Table 1
Directional solidification conditions associated to the primary dendrite spacings as function of cooling rate for the present experiments and those conducted by others researchers.

Author	System	Heat flow conditions	Heat extracting surface	Melt convection	Alloy	$\lambda_1 = f(T_R)^n$
Peres et al. (2004)	upward vertical	transient state	water cooled stainless steel (thickness 3mm)	No	Al-7wt.%Si	$\lambda_1 = 220\ (T_R)^{-0.55}$
Spinelli et al. (2005)	downward vertical	transient state	water cooled stainless steel (thickness 3mm)	Yes	Al-7wt.%Si	$\lambda_1 = 85\ (T_R)^{-0.55}$
This work	horizontal	transient state	water cooled stainless steel (thickness 3mm)	Yes	Al-7wt.%Si	$\lambda 1 = 212\ (T_R)^{-0.55}$

Figure 4 shows a comparison between experimental profiles of primary dendrite spacings as function of cooling rate involving upward, downward, and horizontal directional solidification of Al–7 wt.% Si alloy. It can be seen that in all the cases λ_1 decreases as T_R is increased, as expected.

During horizontal solidification the solutal profile in the mushy zone and in the overlying melt ahead of the dendritic array is not expected to be stable, however, when comparing the mean values of λ_1 obtained in the present study with those from the upward vertical experiments similar results can be observed, i.e., thermosolutal convection during horizontal growth seems to have no noticeable effects on primary dendrite arm spacings for the solidification conditions assumed. On the other hand, it is well known that during downward growth the denser liquid formed in the interdendritic region and at the tip tends to flow downward into the bulk liquid providing melt convection so that for a same cooling rate, the primary spacings are reduced (about 2.5 times) for conditions of downward vertical solidification. According to Spinelli *et al*. (2005), the upward growth aids the radial transport of material and leads to a larger spacing, and the downward growth aids solute rejection and the need for lateral segregation, thus reducing the primary dendrite spacing. Similar tendencies of reduction of λ_1 have been reported recently by Nogueira *et al*. (2012).

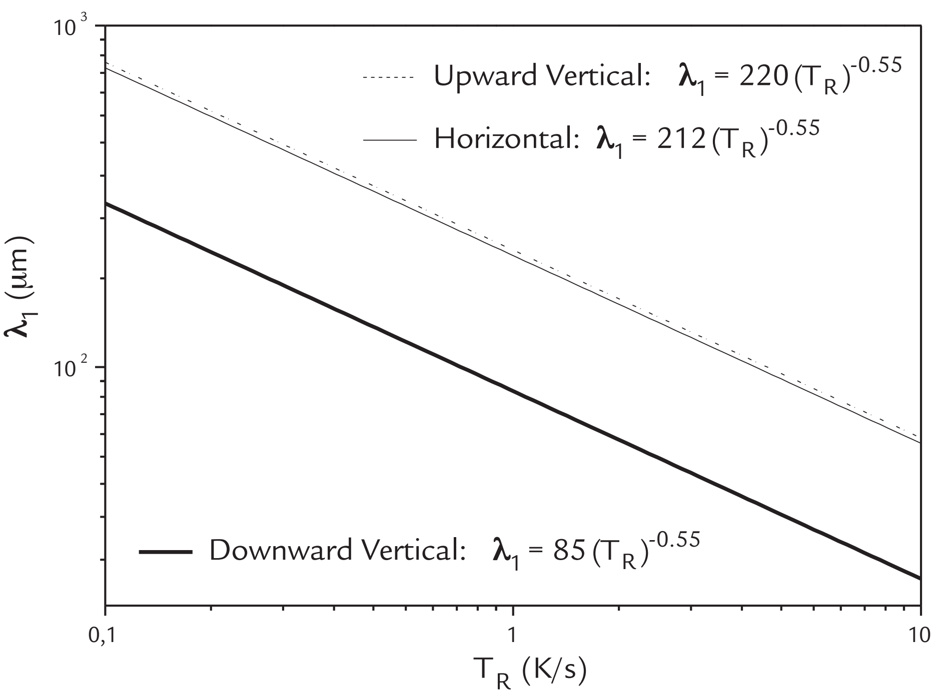

Figure 4
Primary dendrite arm spacings as a function of cooling rate for Al–7wt.%Si alloy.

4. Conclusions

Experiments were conducted in order to analyze the influence of growth rate (V_L) and cooling rate (T_R) on the primary dendrite arm spacings (λ_1) during the horizontal transient directional solidification of Al-7wt.%Si alloy in a carbon steel mold with the thermal contact condition at the stainless steel heat extracting surface being polished cooled. The following major conclusions are derived from this study:

1) The present theoretical–experimental investigation was capable of predicting satisfactorily the experimental variation of primary dendritic spacings of Al–7wt.%Si alloy with both growth rate and cooling rate.

2) Primary dendrite arm spacings were observed to increase as the growth rate or the cooling rate decreased, as expected. A power law function characterizes the primary spacings variation with growth rate with an index of -1.1 as well as a -0.55 power law characterizes the variation of these spacings with cooling rate. It was found that the same –0.55 power law characterizes the experimental variation of primary dendritic spacings with cooling rate in systems with different configurations in the solidification conditions assumed.

3) Thermosolutal convection during horizontal growth seems to have no noticeable effects on primary dendrite arm spacings of the investigated alloy, however, during downward growth for a same cooling rate, the primary spacings are reduced about 2.5 times.

4) A good approximation was observed between the experimental results obtained for the primary dendritic spacings in this work and those calculated by Bouchard-Kirkaldy's model as well as with the theoretical values of the upper limit obtained by Hunt-Lu's model.

5) Aluminum alloys with silicon contents between 5 and 13% are used in engineering components that are supposed to be exposed to critical wear conditions such as engine parts, cylinder blocks and heads, pistons, water-cooled jackets, etc. In this context, this study may contribute to a better understanding of the thermal characteristics and processes occurred in the Al-Si alloys. The achieved results can be used for liquid metal processing in science and industry aiming at designing of a required alloy microstructure and mechanical properties of these alloys.

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