CHAPTER 173

Primary interphase dendritic growth via unsteady-state horizontal solidification of an Al-Cu-Nb alloy

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ABSTRACT
Aluminum and its alloys, compared to steel, have a higher strength/weight ratio, good electrical and thermal conductivity, and better corrosion resistance. Among the various aluminum alloys registered today, we can highlight those that make use of copper, the third most consumed metal in the world. In this context, niobium stands out, which plays an important role in the production of metallic alloys due to its high melting point, resistance to acid attack, and superconductivity at high temperatures. In recent decades, several studies have been carried out to establish the relationship between the thermal solidification parameters and typical as-cast structure in macrostructural and microstructural scales in aluminum alloys, aiming to optimize the properties of these alloys. In this sense, the main objective of this work was to investigate the effects of heat flow parameters, such as growth and cooling rates (V_L and T_R), on primary interphase dendritic growth ($\lambda_{1\alpha}$) in equiaxed dendrites in Al-3Cu-0.5Nb (wt.%) alloy (wt.%), which was horizontally solidified in a recent study. The $\lambda_{1\alpha}$ variation with V_L and T_R has been characterized by mathematical equations given by the general expressions $\lambda_{1\alpha}$ =Constant.$(V_L)^{-1.1}$ and $\lambda_{1\alpha}$ =Constant. $(T_R)^{-0.55}$, which represents the interphase dendritic growth laws, where the exponents -0.55 and -1.1 are in absolute agreement with the primary spacing growth laws in columnar dendrites.

Keywords: Unsteady-state horizontal solidification, Thermal parameters, Primary interphase dendritic growth, Al-Cu-Nb alloys.

1 INTRODUCTION

It is known that Brazil stands out for its significant participation in the world production of aluminum and its alloys. It is the fifteenth-largest producer of primary aluminum and the fourth-largest producer of bauxite, with the state of Pará representing about 89.5% of this product [1]. China and Australia are also countries that stand out. In the Brazilian domestic market, aluminum is mainly used by the transport industries, such as automobile and aeronautics, and packaging, which are followed by the electricity, civil construction, consumer goods, and machinery segments, among others [1-3].

Another metal, niobium (Nb), on which Brazil practically has a monopoly, which still does not have perfect substitutes. Almost all world reserves of this metal, 98.2%, are in Brazil, which is also the largest producer of the element, representing more than 90% of the world's total, according to data from the National Mining Association [4]. The main application of niobium is in the formation of micro-alloyed steels, finding applications in civil construction, mechanical industry, aerospace, naval, automotive, oil and gas pipes, and oil platforms, among others, and it is evident, therefore, how significant it would be for the country to discover new applications that could increase the demand for the metal and increase its added value. Hence, the importance of scientific research for the development of new materials with potential possibilities for future applications in the transformation industries is urgent [4].

Relative to steel, aluminum alloys have a higher strength-to-weight ratio, good electrical and thermal conductivity, and better corrosion resistance. Its disadvantages include a low mechanical strength, especially at high temperatures, as well as a low tensile strength, ranging between 90 and 180 MPa, which ends up restricting its application as a structural material and generally limits it to components of thermal and electrical systems, where it is possible to benefit from its high conductivities without a great requirement about mechanical properties [5-7]. Therefore, it is necessary to improve some of its properties to have better performance and applicability in the industry [6-13]

Among the hundreds of registered aluminum alloys, those of the Al-Cu and Al-Si systems stand out, which are the most used by the automotive and aerospace industries. In the case of Al-Cu alloys, those of greatest industrial interest are the thermally treated ones, in which Cu contents are in the range of 2 to 5% [9,10]. These alloys are known as dura-aluminum and belong to the 2XXX (wrought) and 2XX.X (cast) series in the Aluminum Association classification [2] and are among the oldest aluminum-based alloys. They are widely used in the manufacture of components in the aeronautical and automotive industries, such as aircraft leading edges, structural parts, cylinders, pistons, and engine blocks [9,10,12].

Studies have been carried out with alloys of the duralumin series, which are binary, ternary, or quaternary multicomponent alloys, which have in their composition copper with the addition of silicon, magnesium, titanium, nickel, and others that provide aluminum with excellent mechanical resistance at high temperatures, especially with heat-treated alloys. Niobium, for example, has been one of those elements that, in recent studies, has been investigated as an added element in Al alloys [14-22].

Considering the aforementioned highlights of aluminum-based alloys and observing the continuous development of research related to niobium and its importance for Brazil, as well as due to the scarcity of relevant information on the effects of Nb composition, as well as of solidification path of these alloys, this work as main goal to investigate the effects of thermal solidification parameters, such as the growth and cooling rates (V_L and T_R) on the primary dendritic microstructural scale length of the Al-3Cu-0.5Nb alloy (wt.%).

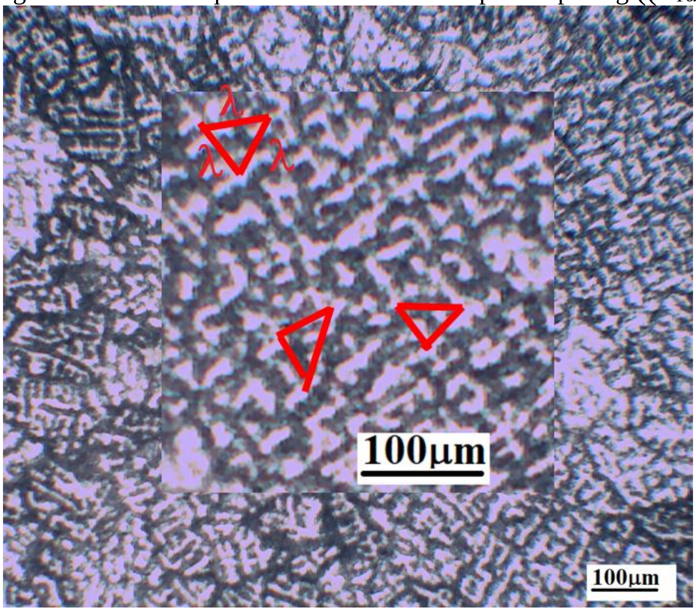
2 EXPERIMENTAL PROCEDURE

The studied alloy, the horizontal solidification experiment, and thermal analyzes to determine the desired thermal parameters (V_L and T_R) were obtained in works recently published by our research group [15,16]. During the preparation of the alloy, because Nb has a very high melting point (~ 2468 °C), which is much higher than that of the other constituent elements of the alloy, Al and Cu, its insertion into the liquid metal occurred last, given the diffusion mechanism under high temperatures for its integration as the second solute in the liquid matrix of the solvent (Al) [16].

The thermal data acquisition system used during the solidification process consisted of a temperature recorder (FieldLogger) connected to a computer and data recording software that receives these values and converts them into a notepad in the form of ordered pairs (T, t). This notepad was imported into another data processing software (OriginPro), where the thermal solidification profiles were plotted, and from the same, the experimental V_L and T_R values were determined [6-10,15,16,23].

Cross-sectional as-cast samples from the solidified ingot resulting from the work of [15,16] were prepared, considering positions from the heat transfer surface of the ingot mold of the water-cooled solidification device, aiming to evaluate the effects of V_L and T_R on the evolution of the dendritic microstructure, which was quantified by the interphase spacing of the primary dendritic arms ($\lambda_{1\alpha}$) of the Al-rich phase. The measurement of $\lambda_{1\alpha}$, shown schematically in Figure 1, according to References [24,25], was based on the neighborhood criterion. That is, the primary spacing value is equal to the average distance between the centers of the primary dendritic arms. This method is known as the "triangle method ."The assumed $\lambda_{1\alpha}$ values were the averages among 20 measurements performed for each sample from the cooled mold plate.

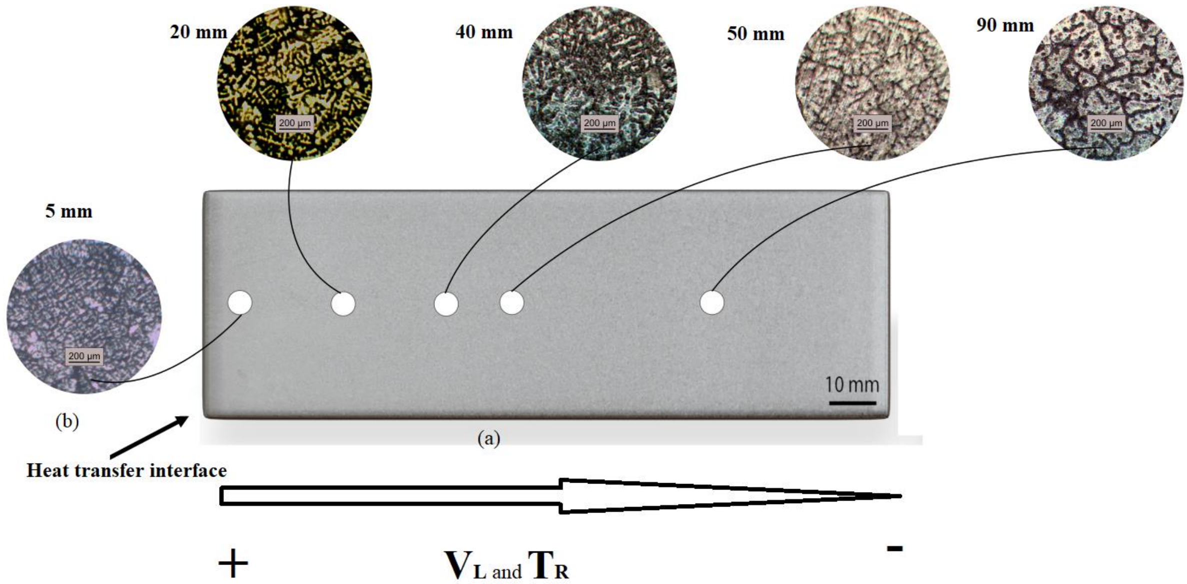
Figure 1. The technique used to measure interphase spacing (($\lambda_{1\alpha}$)



3 RESULTS AND DISCUSSIONS

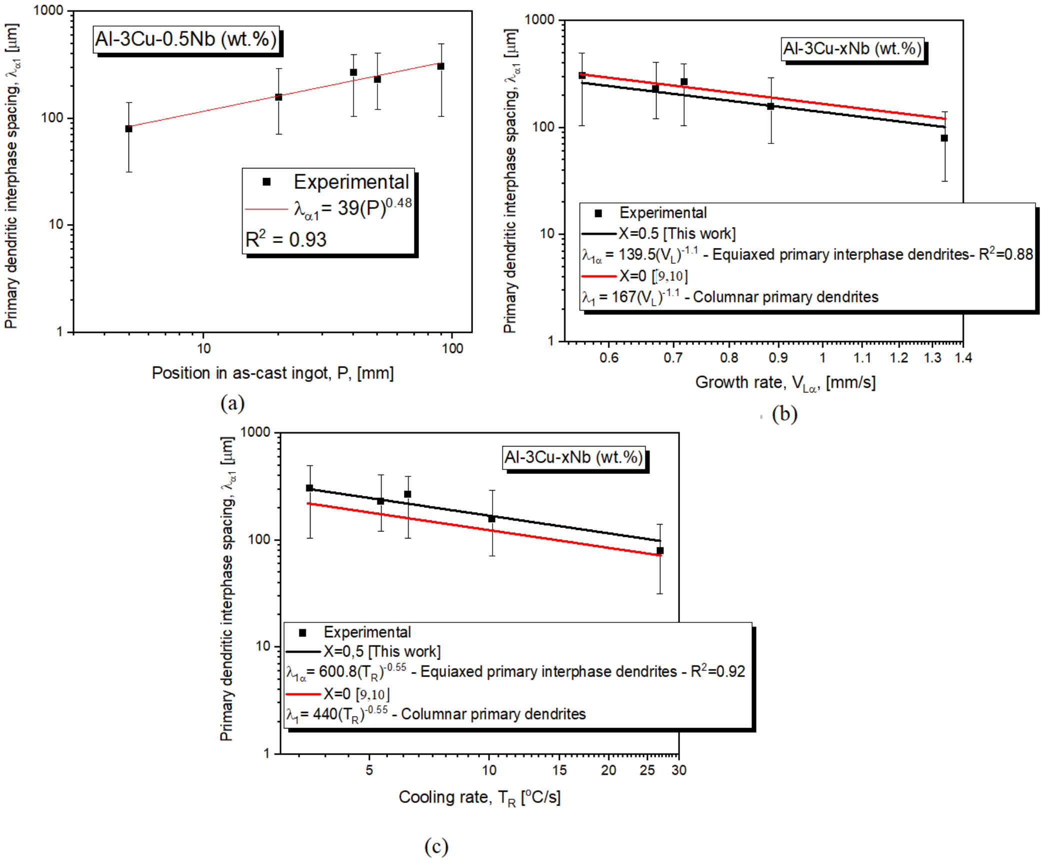
The effects of the cooling system promoted by the horizontal solidification device were evaluated on the evolution of the dendritic microstructure along the length of the as-cast ingot, as shown in Figure 2. As can be seen, the macrostructure consisted of fine equiaxed grains along the length of the ingot, and finer and coarser dendritic microstructures was obtained for positions closer and farther from the heat transfer interface (cooling base) as growth and cooling rates became higher and lower, respectively.

Figure 2. Typical solidification structures of Al-3Cu-0.5Nb alloy (wt.%) solidification in scales: (a) macrostructural, obtained by Dillon [15,16], and (b) microstructural showing the primary interphase dendrites.



Dillon et al. [15,16] carried out thermal analyzes resulting from the horizontal solidification process under the same conditions assumed in this work and proposed mathematical expressions to correlate the thermal solidification parameters (V_L and T_R) as a function of the position in the as-cast ingot, given by $V_L=2.17(P)^{-0.3}$ and $T_R=82.8(P)^{=0.7}$. It could be noticed that the V_L and T_R values gradually decrease with the advance of solidification due to the increasing formation of the solid layer that promotes resistance by thermal conduction, thus influencing the dendritic microstructures shown in Figure 2b. The interphase spacing measurements ($\lambda_{1\alpha}$), as shown in Figure 2, as well as the aforementioned functions V_L=f(P) and T_R=f(P), were used in this study to establish a relationship of $\lambda_{1\alpha}$ as a function of the position in as-cast ingot (P), V_L and T_R, whose results are shown in Figure 3. As noted, equiaxed primary dendrite growth laws represented by power-type mathematical expressions were proposed, which allowed experimentally predicting the dependence of interphase dendritic spacing as a function of the thermal solidification parameters. It can be highlighted in this work that the exponents obtained equal to -1.1 and -0.55 agree with the theoretical and experimental growth laws proposed in the literature for primary dendritic spacing measured in columnar dendrites [6-10,24,25], confirmed by the comparative analysis carried out with the study by Barros et al. [9,10] for a horizontally solidified Al-3wt.%Cu alloy, as shown in Figures 3b and 3c.

Figure 3. Primary dendritic interphase spacings as a function of (a) Position in the as-cast ingot, (b) and (c) growth and cooling rates.



4 CONCLUSIONS

In this study, the effects of thermal solidification parameters were investigated on primary dendritic interphase spacings during horizontal solidification of the Al-3Cu-0.5Nb alloy (wt.%); the following conclusions can be drawn:

“The dependence of primary interphase dendritic arm spacings on thermal parameters V_L and T_R for the Al-3wt.%Cu-0.5wt.%Nb alloy was investigated, and the relationships among them have been obtained. Mathematical expressions given by $\lambda_{1\alpha}=139.5(V_L)^{-1.1}$ and $\lambda_{1\alpha}=600.8(T_R)^{-0.55}$ have been proposed to experimentally predict the growth laws of $\lambda_{1\alpha}$ as a function of V_L and T_R. It was observed that the exponents -1.1 and -0.55 obtained, suggested for columnar dendrites, can also be applied to characterize the experimental variation of $\lambda_{1\alpha}$ with V_L and T_R values for equiaxed interphase dendrites, respectively”.

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