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APPLICATION OF A MATHEMATICAL MODEL OF SECONDARY DENDRITIC GROWTH SOLIDIFICATION FOR BINARY ALLOYS: VALIDATION ON A HORIZONTALLY SOLIDIFIED DILUTED AlCuNb TERNARY ALLOY

Thiago M. Dillon[1], Otavio L. Rocha[1,2*], Helder C. Rodrigues[1], Gabriel H. Machado[1], Hugo M. Azevedo[2]

1 – Programa de Pós-graduação em Engenharia de Materiais, Instituto Federal de Educação Ciência e Tecnologia do Pará IFPA), Av. Almirante Barroso, 1155, 66093-020, Brasil, Belém, Pa..
2 – Programa de Pós-graduação em Engenharia Mecânica, Universidade Federal do Pará (UFPA). Rodovia Augusto Corrêa, 66075-10, Brasil, Belém, PA.

otavio.roha@ifpa.edu.br

ABSTRACT

Dendritic morphology is the predominant microstructure in cast products obtained under most solidification conditions, and the prediction of these structures is of great interest for the evaluation and design of the mechanical properties of cast parts. Thus, this work aims to elaborate a theoretical-experimental analysis of secondary dendritic spacing prediction. For that, a horizontal solidification experiment with an Al3Cu0.5Nb alloy was carried out, using a water-cooled solidification device. The resulting as-cast ingot was characterized for structural analysis, and the length of the microstructural scale was quantified by measuring the secondary dendrite arm spacings (λ_2). A mathematical model from the literature, developed by Bouchard-Kirkaldy (BK), that predicts the λ_2 growth via transient directional solidification of binary alloys was used, and the simulated values were compared with the experimental values obtained in this work. The results achieved have suggested the mathematical approach of BK, developed for binary alloys, for application in ternary alloys when the content of the second solute is very diluted, as in the alloy investigated in this study.

Keywords: Unsteady-state *solidification, Dendritic growth model, AlCuNb alloys*

INTRODUCTION

It is known that solidification involves heat transfer and solute transport, which influence the development of both the macrostructure and the microstructure. The prediction of these structures is of great interest for the evaluation and design of mechanical properties of castings. Dendritic morphology is the predominant microstructure in as-cast products obtained under most solidification conditions. In the case of castings that present dendritic structures, a convenient and widely used way to quantitatively characterize the microstructure formed consists of measuring a parameter known as interdendritic spacing, that is, the spacing between the primary (λ_1), secondary (λ_2) dendritic arms. and tertiary (λ_3)[(1-4)].
Several theoretical models have been proposed in the literature that describe the dependence of these parameters on the thermal parameters of solidification, such as growth and cooling rates (V_L and T_R), initial alloy composition, thermal gradient (G_L)[(5-13)], and local solidification time

(t_{SL}). As secondary dendritic spacings can be measured in columnar and equiaxial dendrites as well as determined by local solidification conditions and other microstructural characteristics such as pore and intermetallic phases can segregate within interdendritic regions, it has been indicated as the main microstructural parameter in the quality control of the properties of cast alloys [1-4]. Initially, it has led to the development of theoretical and experimental studies on secondary dendritic arms in directionally solidified Al-based binary [5-12] and ternary [2-4,13] alloys which proposed mathematical relationships of λ_2 with a function of t_{SL} and V_L given by the general formulas λ_2=Constant.$t_{SL}^{1/3}$ and λ_2=Constant.$V_L^{-2/3}$. Bouchard and Kirkaldy [6] derived a mathematical approach, which is very similar to the Mullins and Sekerka [13] temperature gradient–independent marginal wavelength formula, for application in binary alloys, recommended in a calibrated way for future predictions of λ_2 in conditions of steady-state and unsteady-state solidification, which is expressed by:

$$\lambda_2 = 2a_2\pi\left[\frac{4\Gamma/T}{c_0[(1-k)/D]^2}\right]^{\frac{1}{3}}(V_L)^{-2/3} \quad \text{(A)}$$

where a_2 is the calibration factor, c_o is the composition of the solute, T is the fusion temperature of solvent,, and Γ is the Gibbs-Thomson coefficient.

It is also known that aluminum alloys have a higher property/weight ratio, such as electrical and thermal conductivity and mechanical, wear and corrosion, than steel and its alloys[2-4]. Of course, the combination of various properties mainly depends on the addition of alloying elements and their processing such as solidification, mechanical shaping and heat treatment. Among these alloying elements, the most common are Cu, Si, Mg, Mn, and Zn. Al-Cu and Al-Si casting alloys, as examples, have been the best choice as materials for the automotive and aerospace industries[2-4,14,15]. Other elements, such as Ni, Ti and Nb, added to aluminum provide mechanical strength in high temperature applications. As a novelty, Nb, for example, has been investigated as an alloying element added to binary Al-xNb and ternary Al-Cu-Nb alloys[14,16,17].

MATERIALS AND METHODS

In order to correlate the secondary dendritic spacings with the growth rate V_L, horizontal solidification experiments were carried out with the Al3-Cu-0.5Nb (wt.%) alloy. The water-cooled directional solidification device used in the experiments, as well as the thermal analysis performed during the solidification process for the experimental determination of V_L values, and were detailed in recently published works[14], as shown in Figure 1. The thermocouple readings (Figures 1a) have been used to generate algebraic expressions of position, from the heat transfer surface as a function of time, that is, P= f(t) corresponding to the *liquidus* front passage by thermocouples, as shown in black trendline in Figure 1b. It was obtained by the intersection of the *liquidus* temperature lines, T_L with the thermal profiles generated by each thermocouple. The growth rates of the isotherm *liquidus* (V_L) as a function of position were determined using the derivatives of the equations P=2.2.$t^{0.8}$, i.e., V_L=dP/dt, as can be seen in red line in Figure 1b.

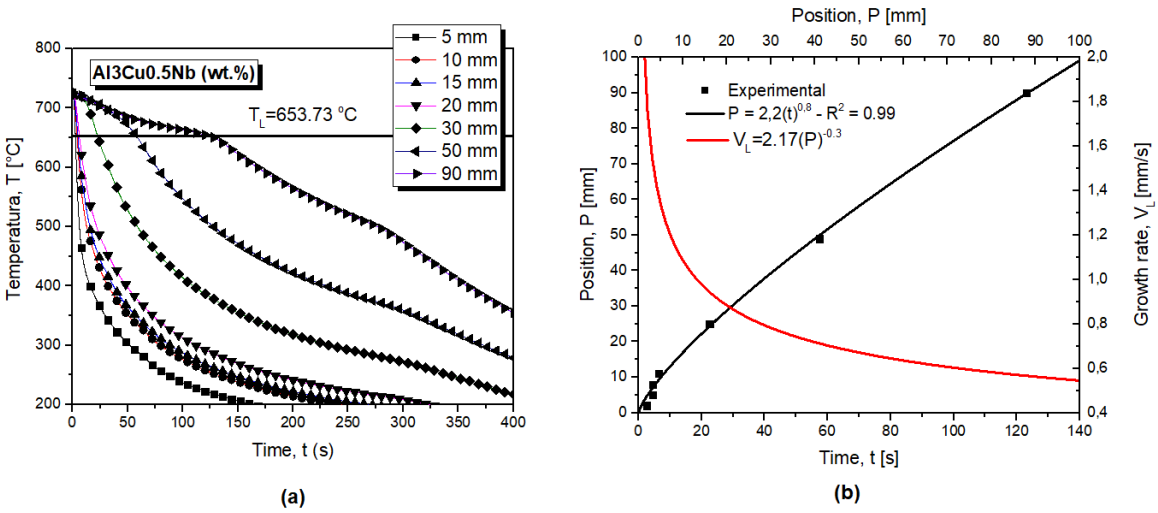

Figure 1. Typical experimental curves of each thermocouple, solidification kinetics, and growth rates for the investigated alloy.

Selected longitudinal sections of the horizontally solidified samples at different positions of ingot from the heat transfer surface were polished and etched with acid solutions of NaOH 5 pct to characterize the microstructure and λ_2 measure. Values for λ_2 were measured by averaging the distance between adjacent side branches on the longitudinal section of a primary dendrite as a function of the distance from the dendrite tip[1-4,6,14,15]. Image processing system MOTIC and the Image J software were used to measure the secondary dendritic arm spacings (~20) independent readings for each selected position.

RESULTS AND DISCUSSION

Table 1 presents the values of the thermophysical properties, used to simulate the theoretical values of λ_2 from Equation A, and the experimental and theoretical λ_2 values were compared and the results shown in Figure 2a. Although the aforementioned mathematical model[6] was developed for binary alloys, it was evidenced an excellent agreement between the results achieved, including considering the correction fact a_2=5 suggested by Borchard-Kirkaldy[6] for binary Al-Cu alloys.

It is important to highlight that Dillon et al.[14] have reported that the Nb content (0.5wt.%) assumed in the final composition of the ternary alloy investigated in this work was found to be completely dissolved in the Al rich matrix, and with Al_2Cu intermetallic phases segregated in the interdendritic regions, which has allowed to assume the thermophysical properties of the Al-Cu binary system, as shown in Table 1.

Typical solidification microstructures are presented in Figure 2b, which clearly show finer dendritic ramifications to positions closer to the transfer surface. heat (cooled base), where higher VL values are reached during the horizontal solidification process.

Table 1. Thermophysical properties used to simulate the Bouchard-Kirkaldy model.

Properties	Symbols	Units	Values
Diffusion coefficient in liquid	D_L	m^2s^{-1}	$3.5x10^{-9}$ (6)
Solute partition coefficient	k_o	-	0.14 (6)
Gibbs-Thomson coefficient	Γ	*K.m*	$2.41x10^{-7}$ (15)
T is the fusion temperature of solvent	T	*K*	933(6)

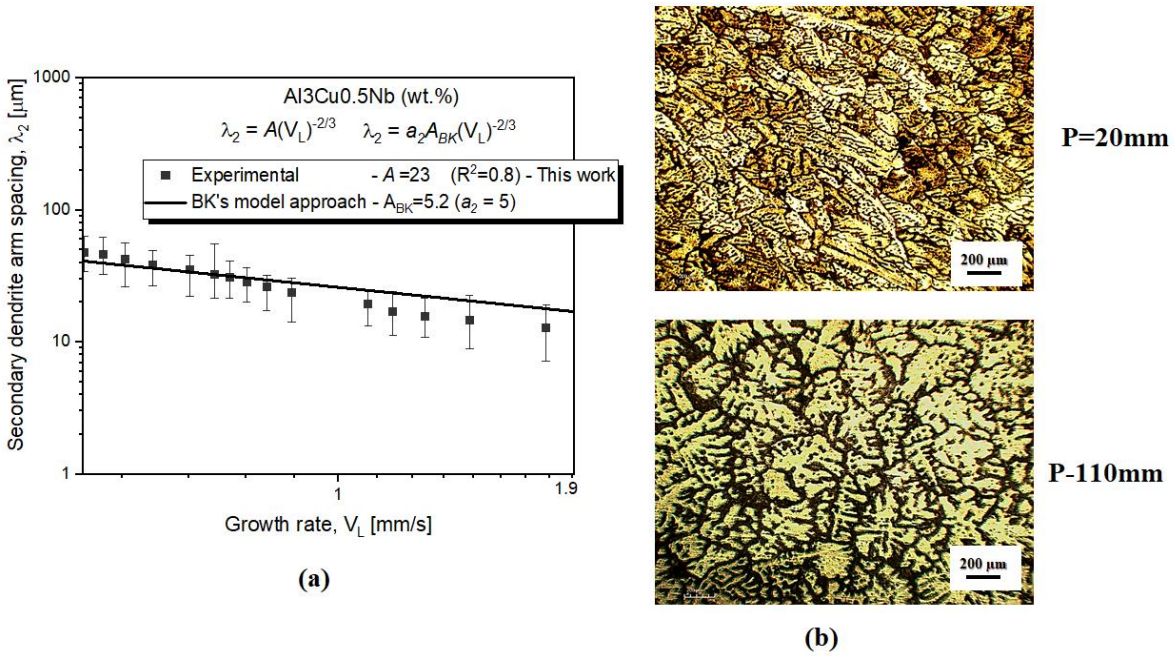

Figure 2. Secondary dendritic spacings: (a) theoretical-experimental analysis, and (b) typical solidification microstructures of the investigated alloy

CONCLUSIONS

In summary, in this work the direct comparison performed between the results of V_L-λ_2 obtained experimentally and simulated by the mathematical model proposed by Bouchard-Kirkaldy for binary alloys has suggested its application to ternary alloys when the content of the second solute is very diluted, as in the alloy investigated in this study. Therefore, for the Al3Cu0.5Nb alloy solidified under the assumed conditions, the results showed that the referred mathematical model could estimate the effects of transient growth rate variations on the scale length of secondary dendritic branches.

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