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Microstructural development in Al–Sn alloys directionally solidified under transient heat flow conditions

Kleber S. Cruz, José E. Spinelli, Ivaldo L. Ferreira, Noé Cheung, Amauri Garcia *

Department of Materials Engineering, State University of Campinas, UNICAMP, P.O. Box 6122, 13083-970 Campinas, SP, Brazil

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Abstract

Despite the wide use of Al–Sn alloys for engineering applications studies on the microstructural development of such materials are rare. Optimized microstructures during the solidification stage of processing can be fundamental for final properties. In the present study, three Al–Sn hypoeutectic alloys were directionally vertically solidified under upward unsteady state heat flow conditions. Primary (λ_1) and secondary (λ_2) dendrite arm spacings were measured along the alloys castings and correlated with transient solidification thermal variables. A combined theoretical and experimental approach has been used to quantitatively determine such thermal variables, i.e., transient metal/mold heat transfer coefficients, tip growth rates, thermal gradients, tip cooling rates and local solidification time. The article also focuses on the dependence of dendrite arm spacings on the alloy solute content. Furthermore, the experimental data concerning the solidification of Al 20, 30 and 40 wt% Sn alloys are compared with the main predictive dendritic models from the literature.

Keywords: Alloys; Solidification; Microstructure; Computer modelling and simulation

1. Introduction

Aluminum-based components are an important example for which the development of optimized microstructures during the solidification stage of processing can be fundamental for final properties and performance. Al–Sn alloys are well known for having excellent tribological and mechanical properties making this kind of alloy system be suitable for engineering applications, particularly in combustion engine pistons and cylinder liners [1–3]. The solid solubility limit of Sn in Al is bellow 0.09 wt% Sn (0.02 at% Sn), Therefore, Al–Sn alloys, which have Sn contents higher than 0.09 wt%, are formed by Sn particles spread over a continuous Al-rich matrix. This type of structural morphology determines the good tribological behavior of the alloy because the tough Al-rich matrix, which is more resistant to high mechanical loads, acts in combination with the Sn particles that function as solid lubricants [4].

Due to the limited solubility of Al–Sn alloys, rapid solidification is expected to affect significantly their mechanical properties through modification of the microstructure. Kong et al. [5] have examined such effect on the microstructure of an Al 12 wt% Sn alloy thermally sprayed onto steel substrates. Despite the wide use of Al–Sn alloys in tribological applications, studies correlating wear and microstructure of such materials are rare. One of the conditions for a final product of required wear-resistant specifications is a microstructure constituted by the Sn-rich eutectic mixture evenly distributed throughout the dendritic matrix [6]. An even distribution of such eutectic in the as-cast microstructure will depend on the growth process of the Al-rich phase.

The thermal variables such as temperature gradient (G_L), growth rate (V_L) and cooling rate ($\dot{T}$) are very important during solidification because of their influence on the formation of the microstructural morphology, which can be cellular or dendritic. In low growth rate conditions, the solid/liquid interface, which is initially plane, can suffer an instability, causing the growth of regular cells in the direction of the heat flow extraction, and practically independent of the crystallographic orientation. If G_L is reduced and V_L increased, the region constitutionally undercoo-

* Corresponding author. Tel.: +55 19 35213320; fax: +55 19 32893722.
E-mail address: amaurig@fem.unicamp.br (A. Garcia).

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Table 1
Casting materials used for experimentation and the corresponding thermophysical properties

Properties	Symbol (units)	Al–20 wt% Sn	Al–30 wt% Sn	Al–40 wt% Sn
Thermal conductivity (solid)	K_S (W m^{-1} K^{-1})	183.8	169.2	154.6
Thermal conductivity (liquid)	K_L (W m^{-1} K^{-1})	79.4	73.6	67.8
Density (solid)	ρ_S (kg m^{-3})	3473.2	3934.8	4396.4
Density (liquid)	ρ_L (kg m^{-3})	3291.6	3753.4	4215.2
Specific heat (solid)	c_S (J kg^{-1} K^{-1})	998.2	906.8	815.4
Specific heat (liquid)	c_L (J kg^{-1} K^{-1})	920.2	837.3	754.4
Latent heat of fusion	L (J kg^{-1})	330140	296460	262780
Liquidus temperature	T_{Liq} (°C)	637	626	616
Solidus temperature (eutectic)	T_{Sol} (°C)	227	227	227
Solute diffusivity	D_L (mm^2 s^{-1})	3.5×10^{-3}	3.5×10^{-3}	3.5×10^{-3}
Partition coefficient	k_o	0.032	0.026	0.021
Gibbs–Thomson coefficient	Γ (K mm)	2.86×10^{-4}	2.78×10^{-4}	2.77×10^{-4}
Liquidus slope	m_L (K wt%$^{-1}$)	1.35	1.24	1.0

led will be extended and the cells begin to change its morphology to a configuration similar to a maltese cross, and the crystallographic factor starts causing a significant effect. With the increase of V_L, cells begin to present side perturbations, generating the side branches, which define the dendritic structure [7].

It is well established that under most conditions of solidification, the dendritic morphology is the dominant characteristic of the microstructure of aluminium alloys. Fine dendritic microstructures in castings, characterized by the dendrite arm spacings, are recognized to yield superior mechanical properties than coarser ones, particularly when considering the tensile strength and ductility [8–11]. Much research has been devoted to the definition of the factors affecting the fineness of the dendritic structure. Numerous solidification studies have been reported with a view to characterizing primary (λ_1) and secondary (λ_2) dendrite arm spacings as a function of alloy solute concentration (C_0), tip growth rate (V_L) and temperature gradient ahead of the macroscopic solidification front (G_L) [12–22]. Reliable spacing predictions in the unsteady-state regime are of prime importance, since this class of heat flow encompasses the majority of solidification processes. Bouchard and Kirkaldy have established a compendium of unsteady-state formulations for primary and secondary dendrite spacings. Recent investigations on primary and secondary dendritic growth of Sn–Pb, Al–Cu alloys under unsteady-state conditions have assessed the performance of such models. The insertion of analytical expressions for tip growth rate and cooling rate into experimental equations has been proposed in order to establish empirical formulae that relate cellular [7] and dendritic [23] spacings with the unsteady-state solidification variables.

The study by Okamoto and Kishitake [24] is the only available in the literature dealing with the experimental dendritic growth during transient solidification of Al–Sn alloys (Al 1, 3 and 5 wt% Sn alloys). Their samples were directionally solidified from bottom to top by dipping the bottom of the crucible in a metal bath. They have concluded that the primary arm spacing is roughly proportional to the square root of the inverse cooling rate, i.e.:

$$\lambda_1 = C(\dot{T}_L)^{-1/2} \tag{1}$$

where C increases linearly with the square root of solute content.

The present investigation was undertaken to characterize the microstructure of Al–Sn alloys. A combined theoretical and experimental approach was applied to quantitatively determine the solidification thermal variables affecting the microstructure, i.e., transient metal/mold heat transfer coefficients, tip growth rate, local solidification time, thermal gradients and tip cooling rate. The article also focuses on the dependence of dendrite arm spacings on such solidification thermal variables and on alloy solute content. At last, the experimental data concerning the solidification of Al 20, 30, and 40 wt% Sn alloys are compared with the main predictive dendritic models from the literature.

2. Dendritic spacing models

Among the theoretical models existing in the literature only those proposed by Hunt and Lu [19] for primary spacings and Bouchard–Kirkaldy [20] for primary and secondary spacings

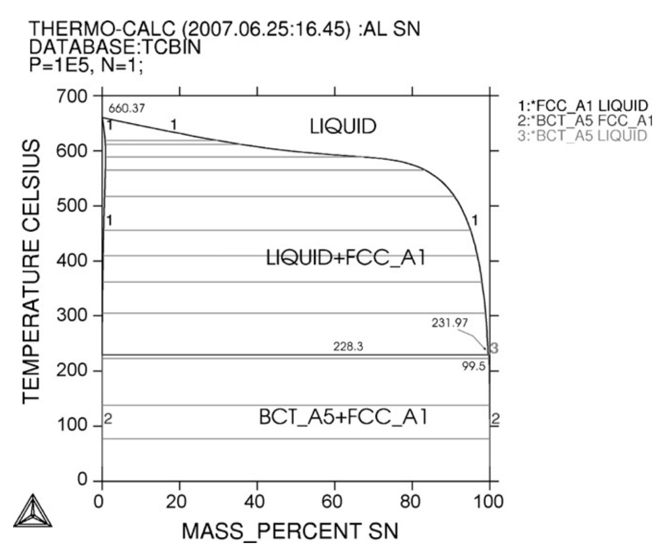

Fig. 1. Al–Sn phase diagram.