Interrelation of Solidification Processing Variables and Microstructure of a Horizontally Solidified Al-based 319.1 Alloy

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In this paper, primary (λ_1) and tertiary (λ_3) dendritic arm spacings of a ternary Al – 7wt.% Si – 3 wt.% Cu alloy casting were characterized and correlated with solidification processing variables: growth rates (V_L), cooling rates (T_C) as well as local solidification times (t_{SL}). Horizontal directional solidification experiments were carried out under transient heat extraction undergoing cooling rates varying from 0.9 ºC/s to 22 ºC/s to be associated with samples having quite different microstructural length parameters. Techniques of metallography and optical microscopy were applied in order to have λ_1 and λ_3 measured. The obtained as-cast microstructures consisted of dendritic α-Al, with Si particles in the aluminum-rich matrix as well distributed along the interdendritic regions in the eutectic mixture interlinked with θ (Al_2Cu) intermetallic phase developing the microstructure α-Al + θ + Si. The results showed that power laws – 1.1, – 0 .55 and 0.55 express the variations of both λ_1 and λ_3 with V_L, T_C and t_{SL}, respectively, for investigated alloy. A comparative study with the Al – 3wt.% Cu alloy from literature was also performed and the results show that the growth law of λ_1 as a function of T_C is represented, for both the investigated alloys, by the mathematical expression given by λ_1 = constant $(T_C)^{-0.55}$.
Keywords: directional solidification, microstructure, Al-based multicomponent alloy.

1. INTRODUCTION

Al-based alloys castings of the ANSI series 319.1 and 333.1 (in which compositions lie mostly within the ranges 5.5 – 10 Si and 3.0 – 4.0 % Cu) have a wide range of applications in engineering components due to its good castability and strength at relatively high temperatures, low coefficient of thermal expansion and good wear resistance [1, 2]. In automotive industry, these alloys have been applied mainly for engine blocks and cylinder heads.

In order to improve mechanical properties, the control of solidification thermal parameters, such as transient metal-mould heat transfer coefficient (h_i), tip growth rate (V_L), temperature gradient (G_L) ahead of the liquidus front and tip cooling rate (T_C), may be a powerful tool in the pre-programming of final properties in Al-based alloys since as-cast microstructures, including dendritic arm spacings, size and distribution of porosity and intermetallic phases, which directly affect mechanical behavior, are strongly dependent on these cooling parameters [3, 4].

As a consequence, solidification processing variables-microstructure correlations have been intensively analyzed for Al-based alloys in a number of studies for upward and downward vertical directional solidification [5 – 7]. The literature, however, is scarce on studies dealing the interesting effects of solutal induced convection on dendritic growth during horizontal directional solidification, particularly for multicomponent alloys [8].

This work aimed at investigating correlations between primary (λ_1) and tertiary (λ_3) dendritic arm spacings and thermal parameters during transient horizontal direction solidification of Al – 7 wt.% Si – 3 wt.% Cu alloy.

2. EXPERIMENTAL PROCEDURE

The casting assembly used in the experiment is shown in Fig. 1. It was designed in such way the heat was extracted only through the water-cooled bottom placed in the lateral mold wall, promoting horizontal directional solidification. A stainless steel mold used was 150 mm long, 60 mm wide, 60 mm high and 3 mm thick. The experiments were performed under a thermal contact condition at the metal/mold interface, corresponding to the heat-extracting surface being polished. When the water flow was initiated the electric heaters were disconnected.

Measurements of temperatures during solidification were made at 5, 10, 15, 20, 30, 50, 70 and 90 mm from cooling interface in the casting via the output of a bank of fine type K thermocouples sheathed in 1.6 mm diameter steel tubes, positioned with regard to the heat extracting surface. The thermocouples were calibrated at the melting point of aluminum exhibiting fluctuations of about 1.0 ºC, all of were connected by a data acquisition system interfaced with a computer. Experiments were carried out with Al – 7 wt.% Si – 3 wt.% Cu alloy, with superheats of 10 % above the liquidus temperature. The ingots were sectioned in specimen's transverse to the solidification direction at 4, 6, 10, 15, 20, 25, 30, 40 and 50 mm from the metal/mold interface. Afterward, they were electropolished and etched with and acid solution composed of 5 mL H_2O, 60 mL HCl, 30 mL HNO_3 and 5 mL HF for micrograph examination. Image processing systems Olympus BX51 and Image Tool (IT) software were used to measure dendrite spacings and their distribution range.

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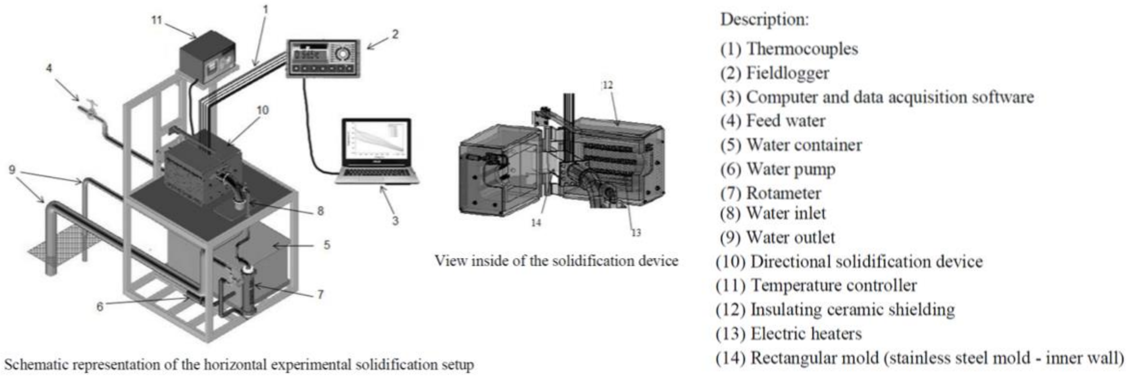


Fig. 1. Schematic view of experimental horizontal directional solidification furnace

The method used for measuring λ_1 values on the transverse section was the triangle method [9, 10]. The λ_3 values were measured on the transverse section by averaging the distance between adjacent side branches [11].

3. RESULTS AND DISCUSSION

Cooling curves for the eigth thermocouples inserted into the casting during solidification of Al – 7 wt.% Si – 3 wt.% Cu alloy are shown in Fig. 2. In Fig. 3 can be seen a plot of position from the metal-mold interface as a function of time corresponding to the liquidus front passing by each thermocouple.

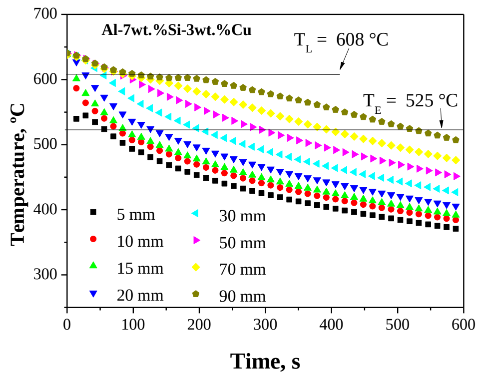


Fig. 2. Thermal profiles obtained for studied Al – Si – Cu alloy

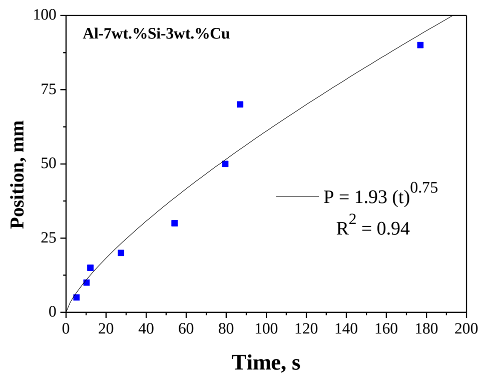


Fig. 3. Experimental position of liquidus isotherm from the metal-mold interface as function of time

The derivative of this function with respect to time has yielded values for V_L, shown in Fig. 4. It can be seen that V_L values decrease with distance from the metal-mold interface, as expected. T_C profile, also indicated in Fig. 4, was calculated by considering the thermal data recorded immediately after the passing of the liquidus front by each thermocouple [9, 12]. It was found that the water-cooled mold imposes higher values of growth rate and cooling rate near the metal-mold interface and a decreasing profile along the casting due to the increasing thermal resistance of the solidified shell with distance from the cooled surface, as expected. The t_{SL} values are presented in Fig. 5, which was determined by difference between the time of passage of the solidus isotherm and the time of passage of the liquidus isotherm for a given point in the casting.

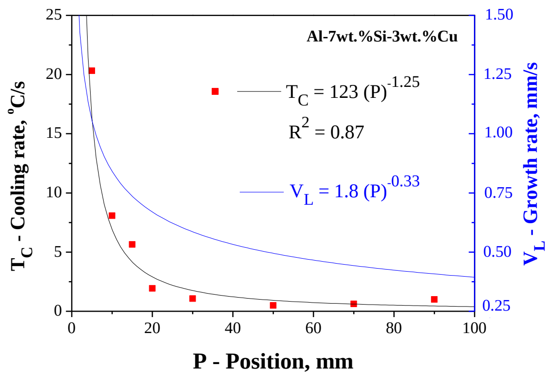


Fig. 4. V_L and T_C as functions of position from the cooling interface

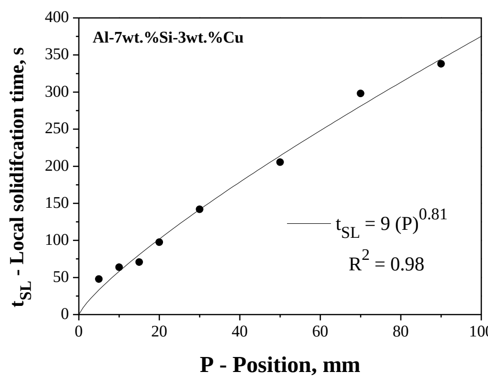


Fig. 5. t_{SL} as a function of position from the cooling interface

In Fig. 6 the macrographs of solidification structure obtained in this study are presented, for the investigated alloy, solidified under superheat of 10 % above liquidus temperature (608 ºC). It is observed that the columnar to equiaxed transition (CET) is not sharp, i.e., CET occurs in a zone rather than in a plane parallel to the chill wall, where both columnar and equiaxed grains coexist.

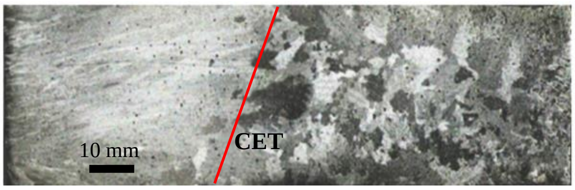
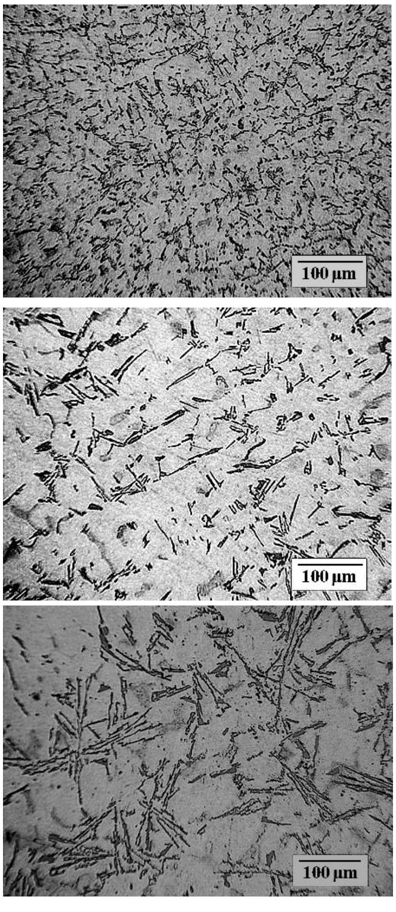


Fig. 6. As-cast solidification macrostructure

The behavior of the solidification thermal variables affects directly the observed experimental values of λ_1 and λ_3 as shown in Fig. 7, where microstructures of transverse section of samples at 4, 25 and 50 mm from metal-mold interface are presented.



P = 4 mm

V_L = 1.1 mm/s
T_C = 22 °C/s
t_{SL} = 27.7 s

λ_1 = 90 µm
λ_3 = 17.8 µm
λ_1/λ_3 = 5.05

P = 25 mm

V_L = 0.62 mm/s
T_C = 2.2 °C/s
t_{SL} = 122.1 s

λ_1 = 501 µm
λ_3 = 36.8 µm
λ_1/λ_3 = 13.6

P = 50 mm

V_L = 0.9 mm/s
T_C = 1.22 °C/s
t_{SL} = 214.0 s

λ_1 = 672 µm
λ_3 = 45 µm
λ_1/λ_3 = 14.9

Fig. 7. Solidification microstructures of transverse section

These microstructures of transverse sections can be characterized by α-Al phase of dendritic morphology, with Si particles in the aluminum-rich matrix as well distributed along the interdendritic regions in the eutectic mixture interlinked with Al_2Cu intermetallic phase developing the microstructure α-Al + Al_2Cu + Si. It can be observed in the as-cast microstructures that Si particles in the interdendritic regions have a plate-like morphology. It can be also observed that the dendrite arm spacings (λ_1 and λ_3 values) were sufficiently distinct to make reasonably accurate measurements along the casting length.

As λ_1 and λ_3 values are strongly dependent on V_L, T_C and t_{SL}, which vary with time and position during solidification, λ_1 and λ_3 averages were plotted as a function of these thermal variables in Fig. 8, Fig. 9 and Fig. 10.

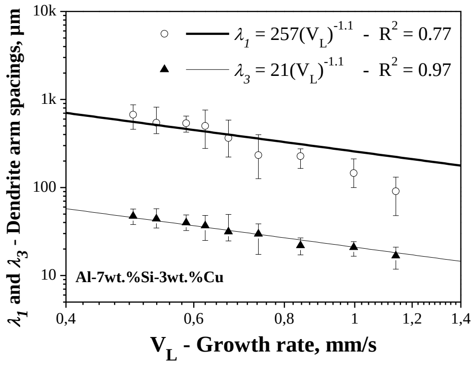


Fig. 8. λ_1 and λ_3 values as a function of V_L

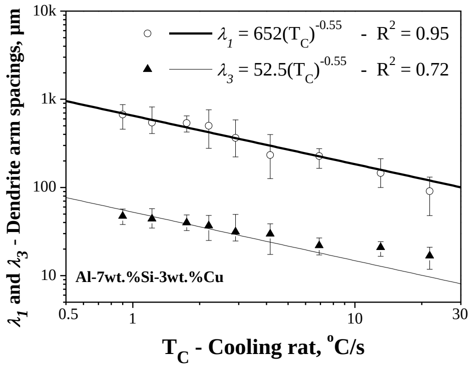


Fig. 9. λ_1 and λ_3 values as a function of T_C

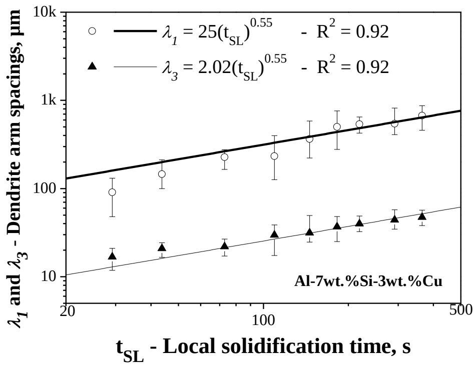


Fig. 10. λ_1 and λ_3 values as a function of t_{SL}

The average spacings along with the standard variation are presented in these figures, with the lines representing experimental power function laws fit with the experimental points. It can be seen that – 1.1, – 0.55 and 0.55 power laws characterize the λ_1 and λ_3 variations with the V_L, T_C and t_{SL}, respectively. This is in agreement with observations reported by Sá *et al.* [13], Rocha *et al.* [9] and Rosa *et al.* [11] that exponential relationships $\lambda_{1,3}$ = constant $(T_C)^{-0.55}$ best generate the experimental variation of tertiary and primary dendritic arms with the cooling rate during upward and downward vertical transient directional solidification of binary Al-Cu alloys, respectively, as well as the experimental results obtained by Araújo *et al.* [14] to Al – 3 % Cu – 5.5 % Si alloy solidified under the same conditions of this work. The multiplier obtained in this work can be associated with the convective effect of solute-rich liquid flow, as well as the influence of the direction of the gravity vector which is perpendicular to the direction of advance of solidification interface.

With a view to analyzing the effect of Si element in binary Al – 3 wt.% Cu alloy on the length scale of the dendritic microstructure (λ_1) the average, maximum and minimum values of the correlation between λ_1 and T_C of this work are plotted in Fig. 11 and compared with the experimental equations obtained by Barros *et al.* [15], which works have been developed to horizontal directional solidification. When comparing the mean values of λ_1 obtained in the present study with those reported recently by Barros *et al.* [15] (see Fig. 11) similar growth laws can be observed, i.e., the addition of Si in the Al – 3 wt.% Cu alloy seems to have no noticeable effects on reduction in the length scale of the λ_1 values during horizontal directional solidification, since the average of λ_1 values observed in Al – 3 wt.% Cu alloy are between the λ_1 minimum values obtained in investigated alloy of this work.

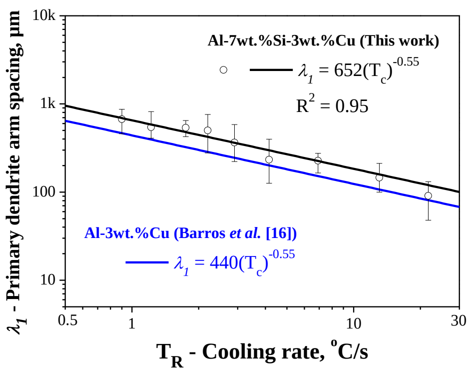


Fig. 11. A comparison among the results obtained in this work with those obtained by Barros *et al.* [15]

4. CONCLUSION

The following major conclusions can be drawn from this study, in which Al – 7 wt.% Si – 3 wt.% Cu alloy has been directionally solidified under transient conditions:

1. Under transient horizontal solidification conditions, the primary dendritic spacing was observed to decrease when tip growth rate and cooling rate are increased.
2. Power law functions characterize the experimental variation of λ_1 and λ_3 with V_L with an index of – 1.1, – 0.55 power law functions characterize the experimental values of λ_1 and λ_3 with T_C, as well as an index of 0.55 characterize the experimental values of dendritic spacings with t_{SL} in systems with different configurations.
3. The presence of Si element in the Al – 7 wt.% Si – 3 wt.% Cu alloy did not affect the index of power law function of λ_1 obtained for the Al – 3 wt.% Cu binary alloy.

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