The columnar to equiaxed transition in horizontal unidirectional solidification of the Al 5wt% Cu under unsteady state heat flow conditions.

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Abstract

Experiments were conducted to examine the columnar to equiaxed transition (CET) during solidification of horizontal directional alloy Al 5 wt% Cu as a function of solidification parameters such as temperature gradients (G_L), growth rates (V_L) and cooling rates (T_R). To this end, an experimental apparatus was used for solidification under unsteady state heat flow conditions. An experimental approach is developed to quantitatively determine the solidification thermal variables considered. The results have supported a proposed criterion based on a critical value of cooling rate. The observation of macrostructures indicated that the columnar to equiaxed transition occurred in a plane parallel to a critical cooling rate of about 5.2 K / s. A comparative analysis between the present results and those of the literature to examine the proposal of the appearance of CET during upward vertical solidification is conducted.

Keywords: *solidification, columnar to equiaxed transition, thermal parameters of solidification, alloy Al 5 wt% Cu.*

1. INTRODUCTION

Many of the mechanical properties of metallic alloys depend on the size and distribution of grains in the structure which is almost determined during the solidification process castings (Doherty , et al, 1977; Gandin, Ch.-A, 2000; Mahapatra et al. 1987; Wang et al. 1994; Siqueira et al, 2002 e 2003; Willers et al, 2005 and Canté et al, 2007, Silva et al, 2009). However, despite the history of investigation of solidification, many aspects of the physics of this phenomenon remain unclear. Aspects of forming of various types of micro and macrostructures in solids obtained, the physical mechanisms of which remain to a large degree unclear, for example, are of particular importance. Since solidification is one of the most important phase transformations in industrial production routes the understanding of the relationship between the thermal variables considered, the prediction of distinct structures and the evaluation and design of mechanical properties is essential for the development of improved methods for quality.

Generally solidification leads to two types of grain morphologies: columnar and equiaxed. The origin of each one has been the subject of numerous theoretical and experimental researches in the field of metallurgy for many years. Columnar grains often grow from near the mold surface, where the thermal gradients are high, and the growth is preferentially oriented in a direction close to the heat flux. When the gradients are reduced near the center of the casting, equiaxed grains grow in all space directions leading to a material with more isotropic macroscopic mechanical properties and a more homogeneous composition field than with columnar structure.

Depending on the application, one type of grain is preferred and thus favoured, e.g. equiaxed grains in car engines and columnar grains in turbine . Thus, equiaxed grains can nucleate and grow ahead of the columnar front causing an abrupt columnar to equiaxed transition whose prediction is of great interest for the evaluation and design of the mechanical properties of solidified products. As a consequence, it is critical for industrial applications to understand the physical mechanisms which control this transition during solidification. Processes where one has to completely eliminate the CET are directional solidification of superalloys and epitaxial laser metal forming (E-LMF), a process for the repair of high value directionally cast single crystal components of aircraft engines. Processes where one wants to enhance equiaxed solidification are welding and continuous casting of steel, in which large investments are made to produce an equiaxed solidification mode in order to obtain the homogeneity of the product.

The CET is considered as an object of high technological relevance with respect to the directional solidification of metallic alloys. This structure transition may be sharp or gradual and it has been reported to be dependent on thermal conditions associated with the casting process, including heat transfer coefficients at the metal-mold interface (hi), tip growth rates (V_L), thermal gradients (G_L), cooling rates (T_R), melt convection, transport of solute, alloy composition, melt superheat, mold temperature, mold design, casting size, casting geometry, and the concentration of nucleating particles, some of which vary with time and position during solidification as observed by Siqueira et al, during the unsteady-state directional solidification of Al-Cu (Siqueira et al, 2002) and Sn-Pb (Siqueira et al, 2003) alloys under different conditions of superheat and hi, and Willers et al (2005) who studied the influence of a rotating magnetic field (RMF) on the unidirectional solidification of Pb–Sn alloys.

The objective of this study is the presentation of experimental results on the CET in one hypoeutectic Al-Cu alloy during the horizontal unsteady-state directional solidification in a cooled mold. A combined experimental approach is applied to quantitatively determine the solidification thermal parameters such V_L, G_L and T_R, which influence the structure transition. A comparative study between the results of this article and those from the literature proposed to investigate the CET during upward vertical solidification of Al-Cu (Siqueira et al, 2002) hypoeutectic alloys is also presented.

2. EXPERIMENTAL PROCEDURE

The Al 5wt% Cu alloy was solidified directionally using the casting assembly schematically shown in Figure 1. It was designed in such a way that the heat was extracted only through the 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. The thermal contact condition at the metal/mold interface was also standardized with the heat extracting surface being polished.

The alloy was melted in situ and heated until a superheat of 5% above the liquidus temperature (T_{Liq}) using an electrical furnace. 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°C and thus inducing a longitudinal heat transfer from the mold. Solidification occurred dendritically from the lateral chill surface, forming a columnar structure.

Experiments were performed with Al 5wt% Cu hypoeutectic alloy.

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, arranged as shown in Figure 1, 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°C and 1°C respectively, and connected by coaxial cables to a data logger interfaced with a computer. Previous measurements of the temperature field were carried out confirming that the described experimental set-up fulfills the requirement of an unidirectional heat flow in horizontal direction.

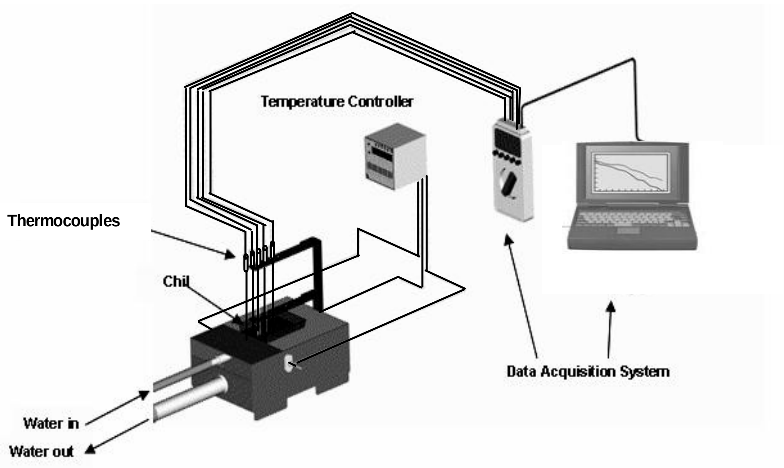

Figure. 1. Scheme of the experimental apparatus for directional solidification of alloy (Silva et al, 2009).

The resultant ingot was sectioned in the longitudinal direction, which is parallel to both the sample axis and the direction of solidification. After this, the metallographic specimens were mechanically polished with abrasive papers and subsequently etched with an acid solution composed of HNO3,3ml e HCl e 90,5ml de H2O to reveal the macrostructure. Etching was performed during approximately 45 seconds. The position of the columnar to equiaxed transition (CET), if any, was located by visual observation and optical microscopy, and the distance from the side of the sample was measured. The chemical compositions of metals that were used to prepare the alloys investigated are summarized in Table. 1.

Tabela 1 - Chemical analyses of metals used to prepare the Al-Cu alloy.

Metal	Chemical composition (wt %)										
	Al	Fe	Ni	Cu	Si	Mg	Pb	Cr	Mn	Zn	Sn
Al	99,68	0,175	0,0148	0,0242	0,103	0,0011	-	-	-	-	-
Cu	-	-	-	99,64	0,09	-	0,002	0,27	-	-	-

3. RESULTS AND DISCUSSION

The directionally solidified structures of alloy with starting melt temperatures (T_V) of 5% above the liquidus(T_L) is shown in Figure 2. The columnar to equiaxed transition occurred at 55 mm from the metal/cooling chamber interface for Al 5wt% Cu alloy.

Figure 2. Solidification Macrostructure.

Experimental cooling curves for the five thermocouples inserted into the casting during solidification of the alloy investigated in this study are shown in Figure 3(a).

The CET is dependent on solidification thermal parameters such as V_L, G_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., 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. The corresponding experimental points of alloy examined are presented in Figure 3 (b).

The derivative of this function with respect to time has yielded values for tip growth rate (Figure 3(c)). The cooling rate (Figure (3(d)) was calculated by considering the thermal data recorded after the passing of the liquidus front by each thermocouple. G_L (Figure (3(e)) has been obtained from the relationship between V_L and T_R, i.e., $T_R = G_L V_L$ (Canté, 2007 e Silva, 2009).

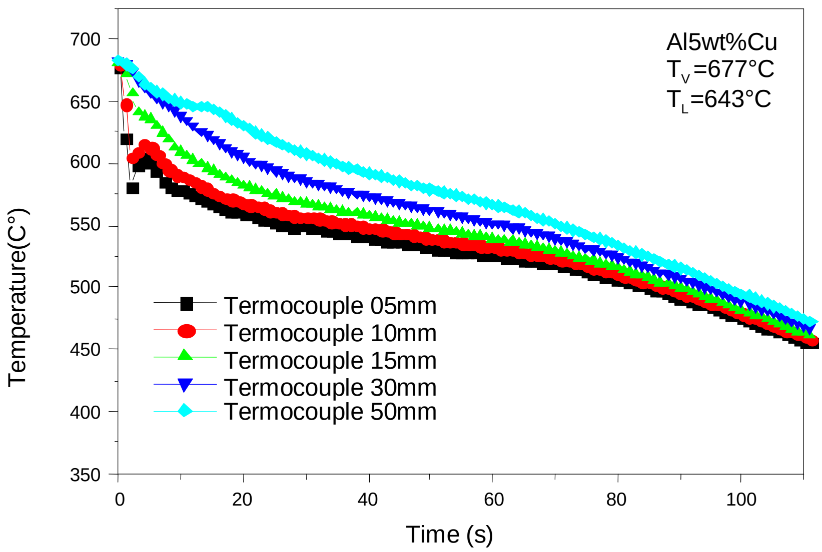

Figure 3(a)- Experimental cooling curves for five thermocouples located at different positions from the metal-cooling.

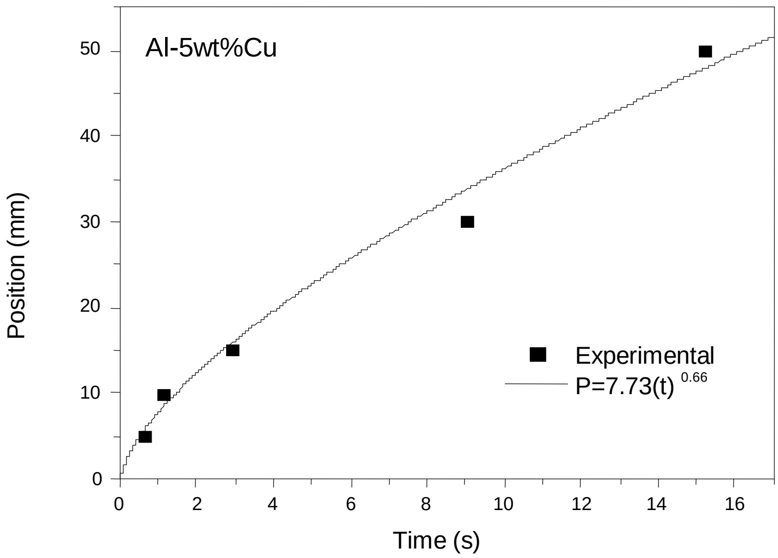

Figure 3(b). Experimental position of liquidus isotherm from the metal/mold interface for Al5wt%Cu as function of time

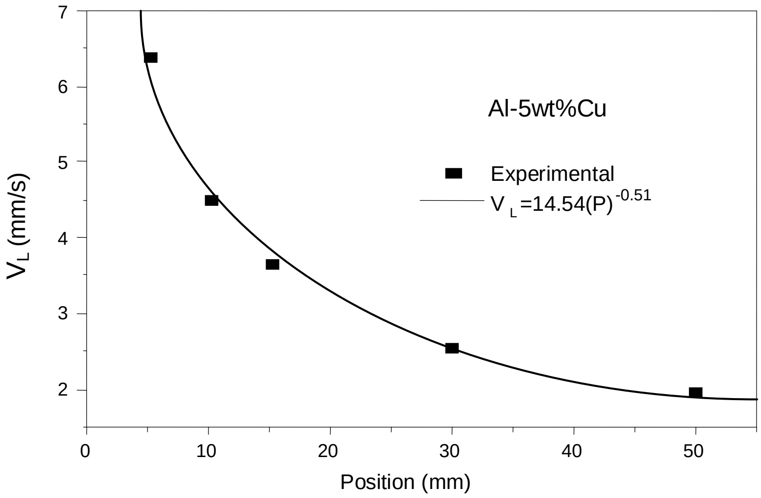

Figure 3(c)- Tip growth rate as a function of position from the metal/mold interface for Al5wt%Cu alloy during horizontal solidification.

Tip cooling rate (K/s)

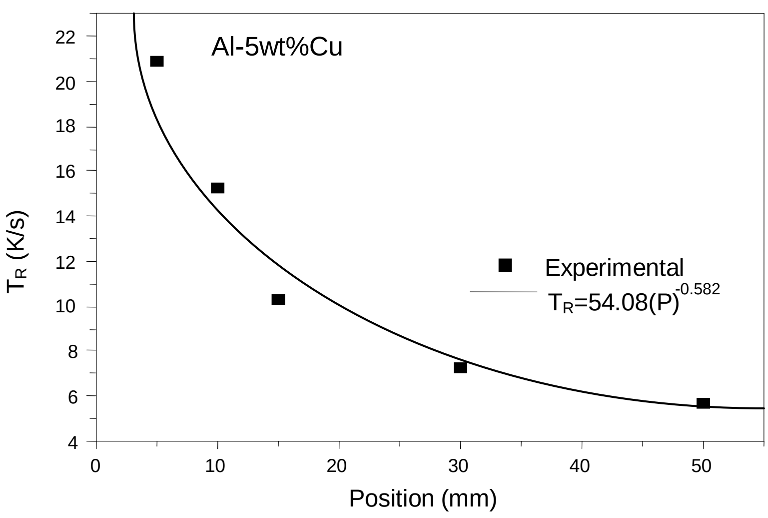

Figure 3(d)- Tip cooling rate as a function of position from the metal/mold interface for Alwt%Cu alloy during horizontal solidification.

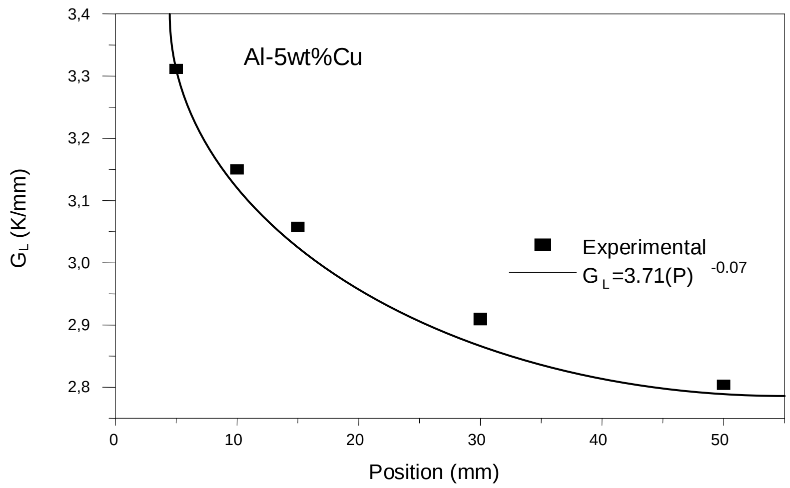

Figure 4(e)- Temperature gradients as a function of position from the metal/mold interface for Al5wt%Cu alloy during horizontal solidification.

Experimental results of CET positions, tip growth rate (V_L), temperature gradient in the liquid ahead of the tip interface (G_L), and cooling rate (T_R) at the transition are listed in Table 2. It can be observed that the structural transition occurred at positions 55 mm from metal/mold interface and cooling rate is of 5.24 K/s . On the other hand, investigations by Siqueira et al (2002), listed in Table 3, on vertically upward solidification of Al 5 wt%Cu alloy, have proposed a CET criteria based on critical cooling rates. The results obtained in the present work suggest that the CET occurs when a critical cooling rate is reached at the dendrite tips. For the investigated alloys the average critical value is of about 0.201 K/s. In the case of horizontal unidirectional solidification, the end of the columnar region is abbreviated as the result of a critical value for the cooling rate that is twenty-six times as high as what was observed during solidification, which does not take the convection effect into account. Rejection of the solute for interdendritic liquid during solidification results in an increase in density for that liquid. Thus, the differences in density can initiate intense convective movements in the liquid. A similar analysis was found by Silva et al (2009) to Sn-Pb alloy, which also compared their results with those proposed by Siqueira et al (2003).

Table 2 – Horizontal Solidification to Al-Cu alloy (this work).

Tv 677 ^oC **CET**	**P (mm)**	**V_L (mm/s)**	**T_R (K/s)**	**G_L (K/mm)**
	55	1.88	5.24	2.8

Table 3 – Upward vertical solidification to Al-Cu alloy (Siqueira et al, 2002).

Tv 680 ^oC **CET**	**P (mm)**	**V_L (mm/s)**	**T_R (K/s)**	**G_L (K/mm)**
	60	0.358	0.201	0.564

4. CONCLUSION

Experiments were conducted in order to analyze the CET occurrence during the horizontal unsteady-state directional solidification of Al-Cu alloy analyzed. The following main conclusions are derived from the present investigation:

1. The basic feature of the CET is that the transition is sharp, i.e., the columnar-to-equiaxed transformation occurs rapidly along a plane parallel to the chill wall.
2. The CET has occurred for V_L equal to 1.88 mm/s and for values of G_L in the melt ahead of the liquidus isotherm equal to 2.8 K/mm.

3. The resulting thermo-solutal convection seems to favor the CET which occurs when a critical T_R is reached at the dendrite tips. For the investigated alloy the CET has occurred for T_R equal to 5.24 K/s.
4. A comparison of the results obtained in the present work with previous investigations concerning the CET in Al-Cu hypoeutectic alloy, conducted under conditions of upward unidirectional solidification, has shown that the proposed criterion based on a critical cooling rate can be applied to the present experimental results;
5. The end of the columnar region during horizontal unidirectional solidification is abbreviated as a result of a twenty-six times higher critical T_R than that verified during upward unidirectional solidification of alloy investigated.

5. REFERENCES

Willers B., Eckert S., Michel, U., Haase, I., Zouhar, G. 2005, The columnar-to-equiaxed transition in Pb–Sn alloys affected by electromagnetically driven convection. Materials Science and Engineering A 402, pp. 55–65.

Wang C.Y., Beckermann C. 1994, Prediction of columnar to equiaxed transition during diffusion-controlled dendritic alloy solidification. Metallurgical and Materials Transactions. 25A, pp. 1081-1093.

Gandin, Ch.-A. 2000, "From Constrained to Unconstrained Growth During Directional Solidification", Acta Materialia, Vol. 48, pp. 2483-2501.

Canté M. V., Cruz, K. S., Spinelli, J. E, Cheung, N., Garcia A. 2007, Experimental analysis of the columnar-to-equiaxed transition in directionally solidified Al–Ni and Al–Sn alloys. Materials Letters 61 pp. 2135–2138.

Mahapatra, R.B., Weinberg, F. 1987 The columnar to equiaxed transition in tin-lead alloys. Metallurgical Transactions 18B 425–432.

Doherty, R.D., Cooper, P.D., Bradbury, M.H., Honey, F.J. 1977, On the columnar to equiaxed transition in small ingots. Metallurgical Transactions 8A pp. 397-402.

Silva, J. N., Moutinho, D. J., Moreira, A. L., Ferreira, I. L., Rocha, O. L.. 2009, The columnar to equiaxed transition during the horizontal directional solidification of Sn–Pb alloys, Journal of Alloys and Compounds, Vol. 478 , pp. 358 -366.

Siqueira, C.A., Cheung, N., and Garcia A. 2002, "Solidification Thermal Parameters Affecting the Columnar to Equiaxed Transition", Metallurgical and Materials Transaction A , Vol. 33 A, pp. 2107-2118.

Siqueira, C.A., Cheung, N., and Garcia A. 2003, "The Columnar to Equiaxed Transition During Solidification of Sn–Pb Alloys", Journal of Alloys and Compounds, Vol. 351, pp. 126-134.

6. ACKNOWLEDGEMENTS

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