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A Comparative study of solidification of Al-Cu alloy under flow of cylindrical radial heat and the unidirectional vertically

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ABSTRACT. In spite of technological importance of solidification of metallic alloys under radial heat flow, relatively few studies have been carried out in this area. In this work the solidification of Al 4.5 wt% Cu cylinders against a steel massive mold is analyzed and compared with unidirectional solidification against a cooled mold. Initially temperature variations at different positions in the casting and in the mold were measured during solidification using a data acquisition system. These temperature variations were introduced in a numerical method in order to determine the variation of heat transfer coefficient at metal/mold interface by inverse method. The primary and secondary dendrite arm spacing variations were measured through optical microscopy. Comparisons carried out between experimental and numerical data showed that the numerical method describes well the solidification processes under radial heat flux.

Keywords: unidirectional solidification, radial heat flow, heat transfer coefficient, aluminum alloy.

Estudo comparativo da solidificação da liga Al-Cu sob fluxo de calor radial cilíndrico e unidirecional ascendente

RESUMO. A despeito da importância tecnológica da solidificação de ligas metálicas sob fluxo de calor radial, relativamente poucos estudos estão sendo realizados nessa área. Neste trabalho, a solidificação da liga Al-4,5%Cu em molde de aço radial cilíndrico é analisada e comparada com a solidificação unidirecional em molde resfriado. Inicialmente, a variação de temperatura em diferentes posições no metal e no molde foram medidas durante a solidificação usando um sistema de aquisição de dados. Essas variações de temperatura foram introduzidas num método numérico para determinar a variação do coeficiente de transferência de calor na interface metal/molde pelo método inverso. Os espaçamentos interdendríticos são determinados a partir das micrografias. Comparações entre variações e temperaturas calculadas numéricas e experimentalmente comprovaram que o método numérico descreve satisfatoriamente o processo de solidificação.

Palavras-chave: solidificação unidirecional, fluxo de calor radial, coeficiente de transferência de calor, ligas alumínio.

Introduction

Due to increasing competition in the foundry market, industries find themselves in a scenario where the cost savings and improvements in the quality of their products is paramount to ensure competitiveness and profitability. The improvement in knowledge of the solidification process is fundamental to the purpose of technology development, for within a methodology based on trial and error, the foundry will not be able to follow the development of other productive areas of industry metal / mechanics. With the aid of experiments and mathematical models to simulate the actual conditions prior to investing directly in the process, can avoid losses in energy, labor, work and material used in the industry (GARCIA, 2001; SILVA et al., 2012).

A literature review shows that in recent years experimental studies developed using unidirectional solidification process with the objective of analyzing the influence of parameters on the solidification structure formation and the generation of defects in metal alloys has been the subject of a large number of jobs and international publications. In the case of solidification in cylindrical radial heat flow, despite the technological importance, few studies have been produced in this area. The theoretical and experimental analysis of solidification in cylindrical molds is complex due to heat flow which causes a divergent solidification front circular converging to a central point (SOUZA et al., 2005a and b; SANTOS et al., 2001).

During solidification with the formation of the gap of this air interface, the heat transfer coefficient can rapidly decrease, making the removal of heat and slowing down the solidification process of the liquid metal. The structure and consequently the properties of a casting depends on the thermal conditions during the solidification, or more precisely the cooling rates, which in turn depend on the heat resistance of this metal/mold interface. Thus, the heat transfer interfacial metal / mold due to its great influence on the rate or speed of solidification of castings, have been studied for many researchers (SILVA et al., 2012; SPINELLI et al., 2012).

The formation of microstructure has been the subject of several studies of many researchers including Melo et al. (2005) who studied the effects of secondary dendrite spacing in the formation of microporosity in Al-Cu alloy, where the variation of dendrite spacing during solidification was determined using the variations in temperature, the speed of advance of the tip of the dendrite, the local solidification time and the thermal gradient from front dendritic obtained by numerical model (MELO et al., 2007; SOUZA et al., 2005a).

Several other researchers via the solidification metals, studied the microstructures resulting from unidirectional solidification radial and under the most diverse geometries, temperature conditions and chemical compositions (GÜNDÜZ; ÇARDILI, 2002; SANTOS et al., 2004).

The objective of this study is related to an experimental analysis of an alloy of Al 4.5%Cu using the solidification process under heat flux radial cylindrical order to determine the variation of heat transfer coefficient in the metal/mold interface, using developed a mathematical model. To achieve this goal have been obtained experimentally during solidification curves of temperature variation in different points in the system metal/mold and from these results determined by the numerical method, the solidification thermal parameters. The main features of microstructures: the dendritic spacing along the cross section during solidification of horizontal cylindrical ingots were determined.

Material and methods

The alloy used in the experimental work belongs to the binary system Al-Cu, respectively, whose composition is shown in Table 1.

Table 1. Chemical composition obtained for the alloy Al-4.5% Cu used in the experiment.

	Al 4,5% Cu				
Symbol	Al	Cu	Fe	Si	others
% in weight	95,16	4,58	0,13	0,09	0,04

The device used for radial cylinder alloy solidification, besides the electric furnace and crucible, had the following equipment: k type thermocouples, data acquisition system and cylinder with argon gas. Figure 1 shows the positioning of the thermocouples in the radial cylindrical mold which are coupled to the data acquisition system.

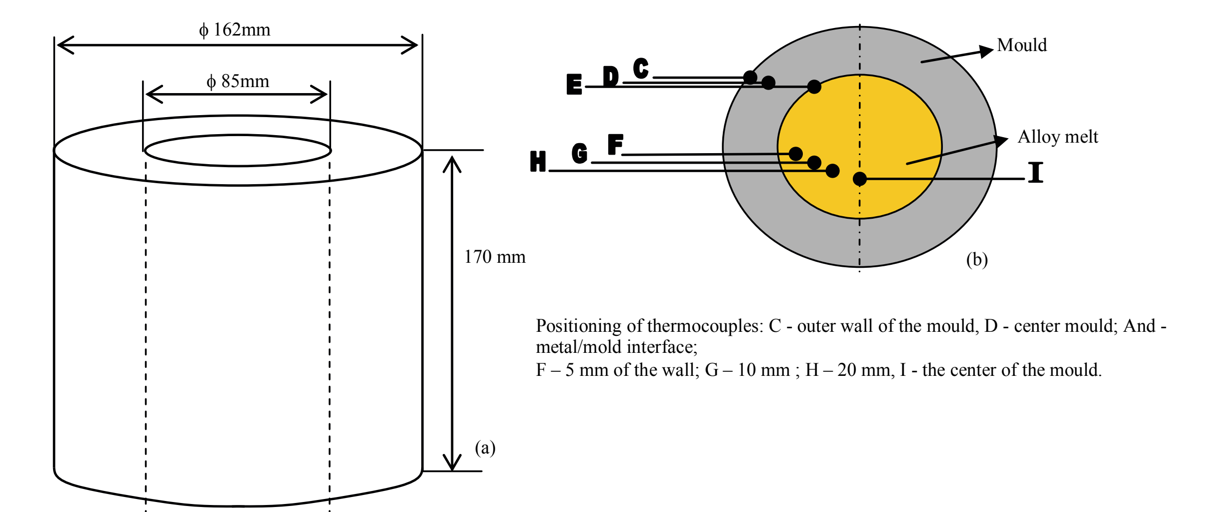


Figure 1. Scheme device for solidification in radial cylindrical steel mold with a polished surface, viewed from the front (a) and from above (b) linked to various thermocouples and data acquisition system coupled to a microcomputer.

The temperature variations against time during the solidification were recorded in a data acquisition system resolution of 12 bits composed of two plates conditioning, one for type K thermocouples 16 and 16 for another type thermocouples S, with a rate acquisition of 10 Hz per channel.

For analysis of the microstructures of the cast billet, a sample was sectioned at various positions in the sample transverse directions: longitudinal and transverse subsequently embedded in polyester resin. After mounting, the samples were abraded in circular mechanical sander, with water as lubricant, following sanding sheets: 100, 220, 320, 400, 600, 800, and 1200. Then the samples were placed in an ultrasonic for 3 minutes and then subjected to mechanical polishing with diamond paste in cloths 6, 1 and 0.25 μm, always placed on ultrasound every change of cloth.

The reagent used to attack the alloy Al-4% Cu 5 is composed of: 90 mL of water, 4.5 mL of nitric acid, 2.7 mL of hydrochloric acid and 1.8 mL of hydrofluoric acid. The samples were dipped for 5 to 8 seconds and rinsed, treated acetone and dried.

To measure the dendrite arm spacings in several samples from the metal/mold interface to region columnar zone the samples were analyzed in an optical microscope Neophot - 32, using the method described by Gündüz and Çadirli (2002). The measurements were performed using the software Q500 MC Leika of Cambridge Ltda, interconnected under a microscope. For the secondary dendrite arm spacing was used the average of the distances between the side branches, measured in longitudinal section of a primary dendrite. For the primary dendrite spacing the average distances between the primary branches, as well as in longitudinal and transverse section.

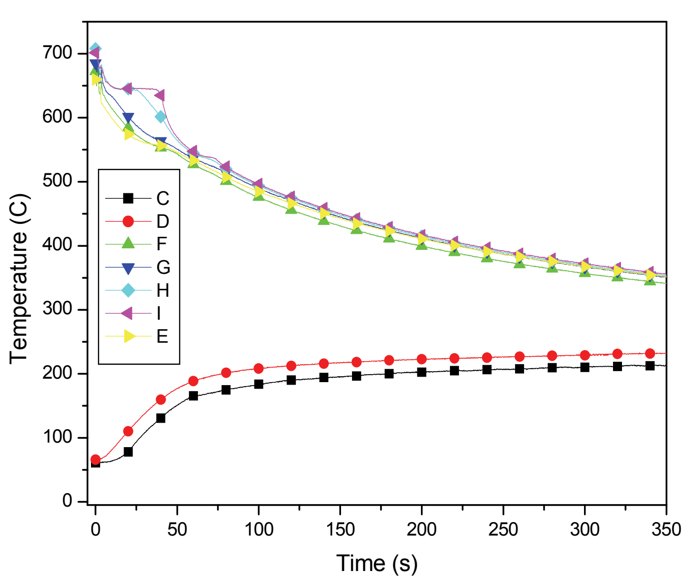
Results and discussion

Cooling curves

As mentioned earlier have been used eight thermocouples at different positions from the mold wall until the liquid metal, according to Figure 1, and a data acquisition system coupled to a computer to obtain the curves of temperature variations against time in different positions. The alloy Al-4 Cu 5% was poured at a temperature of 800°C, approximately, with overheating least 15% in order to ensure complete filling of the mold. Figure 2 shows the cooling curve as a function of time and the caption of the thermocouples used.

In Figure 2 the two lower curves show the results obtained for the outer surface of the mold and at mid-thickness. As can be seen grows until the first 60 seconds, then stabilizes at values close to 200 seconds, allowing for a temperature gradient between the metal and the environment.

In the upper part of the Figure 2 shows the temperature values at various positions of the metal during solidification. It may be noted that although the alloy containing 4.5% copper, and present *solidus* temperature of 560°C, the end of the solidification occurs in the eutectic temperature (548°C) due to solute rejection interdendritic channels.



Thermocouples:

C - the outer surface of a cylindrical mould;

D - center wall of the mold;

E - Metal Interface / Horizontal Template

F - 5mm in liquid metal;

G - 10mm in liquid metal;

H - 20mm in liquid metal; e

I - center of the mould.

Figure 2. Cooling experimental curve for different positions in the liquid metal in the mold and radial cylindrical obtained with type K thermocouples acquisition system and computer temperatures.

One can also observe the result obtained by the thermocouple positioned in the center part (thermocouple I) overheating in liquid metal; is dissipated rapidly after a time interval approximately 15 to 40 seconds. The total time for solidification was 60 seconds approximately.

Heat transfer coefficient in the metal/mold interface

The heat transfer coefficient in the metal/mold interface is a parameter that directly influences the final structure of castings, it is important to know its shape change and know how to treat it. The determination of heat transfer coefficient in the metal/mold interface was done using the experimental temperature at different positions in the metal and the mold inserted into a numerical model which simulates the solidification process in a cylindrical mold. For this, we used a model developed by Melo et al. (2005).

Figure 3 shows the results obtained for the variation of heat transfer coefficient in the metal/mold interface.

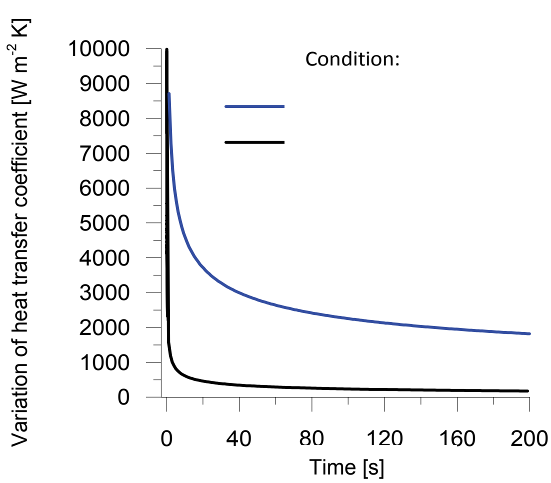


Figure 3. Variation of heat transfer coefficient in the metal/chill interface under unidirectional heat flow and the heat transfer coefficient for metal/mold interface under radial heat flow, was calculated by numerical method.

It can be observed that the variation of heat transfer coefficient in the metal/mold interface under heat flow radially cylinder is initially high and decreases rapidly with time reaching a value of approximately 300 W m^{-2} K is stabilized as a result of the gap air that arises due to the contraction of the metal solidified.

Merely for comparison, together with the results obtained for radial solidification presents the results obtained by unidirectional solidification by Melo, the same alloy in cooled mold. The results indicate that the heat transfer coefficients obtained by cooled mold are much larger, stabilizing at values around of 3000W m^{-2} K (MELO et al., 2005).

This difference can be explained in part by the fact that the vertical unidirectional solidification, a displacement of the sidewall, so that due to gravity and the metallostatic pressure, the solidified layer touches the surface of the copper mold cooled (chill), increasing the contact and thereby reducing the resistance to heat flow increases the heat transfer coefficient.

The variation of heat transfer coefficient with time, in general, can be placed in the following manner (MELO et al., 2005):

$$h = a.t^{-n} \quad (1)$$

where:

h [W/m^2K]; t – the time [s]; a and n are the constants dependent of metal/mold system and solidification conditions obtained in the experiment.

Based on experimental results the equation that describes the variation of heat transfer coefficient in the metal/mold interface is given by (MELO et al., 2005):

$$h = 1677 \cdot t^{-0,485} \quad (2)$$

Experimental and Numerical Analysis

Once determined the variation of heat transfer coefficient as a function of time, values were used to determine, from the numerical method, the curves of variation of temperatures at various points in the solidified metal.

In Figure 4, the curves are numerically compared with the experimental curves. It was found that the heat transfer coefficient in the metal/mold interface are consistent and indicate good agreement, allowing a consistent simulation of the solidification process by means of the numerical method.

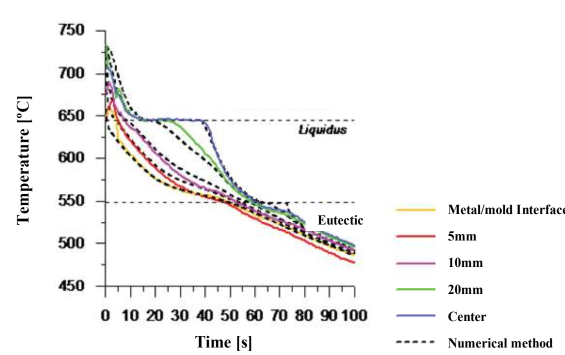


Figure 4. Experimental cooling and numerical curves.

Note: Thermocouple positioned in the metal/mold interface due to experimental problems, the solidification curve there was not complete obtained.

Microstructure

Figure 5 shows micrographs for different positions in the metal/mold interface.

Figure 5 (a) refers to dendritic microstructure of chill grains zone in ingot where there is not grains with definite direction. Figures 5 (b and c) were obtained columnar of ingot in the region where it is observed dendrites growing well defined. In Figure 5 (d) is noted that the microstructure at the center of the ingot is characterized by a structure with equiaxed dendrites without definite direction.

In Figure 6 (a and b) are shown the experimental measurements of the variation of the primary and secondary dendrite arm spacings as a function of distance from the metal/mold interface, the restricted region with columnar structure.

In Figure 6 (a) note that initially there is an increase in primary dendrite spacing with the evolution of solidification to a certain position, then there is a change in behavior with decreasing. These results are consistent with the variation in *liquidus* isotherm velocity which directly affects the primary dendrite spacing and also presents a reversal of behavior.

From the results observed, it is noted that the secondary dendrite spacing does not present a significant variation in the columnar region. This behavior is consistent with the result obtained for the local solidification time which also has a significant variation in the columnar region. As the secondary dendrite spacing depends directly on the local solidification time, it should not also present significant variation in this region.

The values of the secondary dendrite arm spacings by Bower et al. (1966) equation were obtained from the relationship between the spacings secondary and local solidification time, that is (MELO et al., 2005):

$$\lambda_2 = K t_l^{a} \quad (3)$$

where:

t – the time [s], *K* and *a* are constants with values corresponding respectively to 7.5 and 0.39 (GARCIA, 2001).

From the results obtained it can be noted that the secondary dendrite spacing obtained by Bower et al. (1966) equation compared with the experimental data does not vary as shown in Figure 6 (b).

(a) (b) (c) (d)

Figure 5. Microstructures of alloy Al 4.5% Cu under heat radial flow, (a) near the mold wall, chill zone, (b) 15 mm from the metal /mold interface, columnar zone, (c) 25 mm distant from metal/mold interface, columnar zone, (d) center of the mold, the central equiaxed zone.

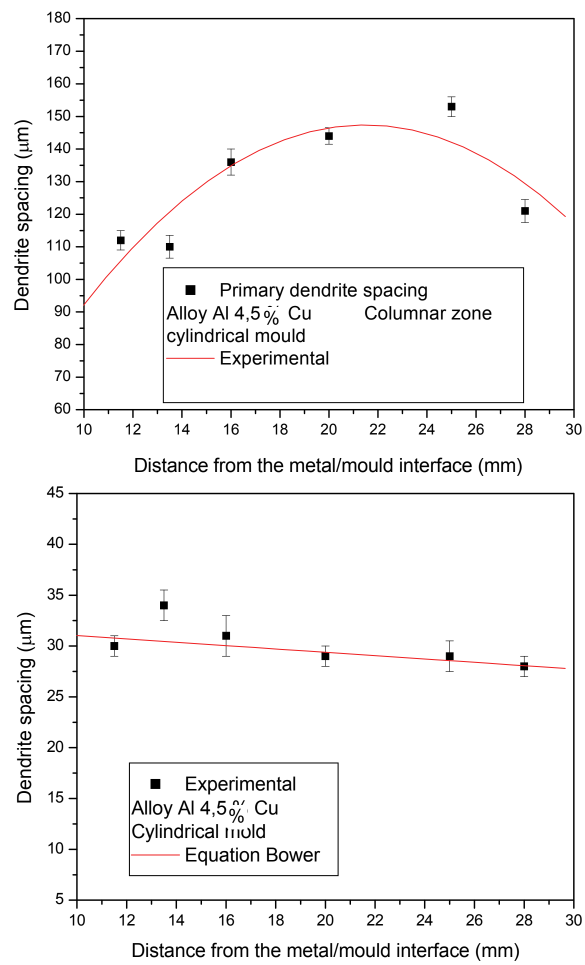


Figure 6. Variation of dendritic spacing distance in relation to the metal/mold interface to the columnar zone (a) primary spacing and (b) secondary spacing, and the experimental equation of Bower et al. (1966).

Conclusion

The theoretical and experimental results obtained with the numerical model, relating to the solidification radial cylindrical allow the following conclusions to be drawn:

The heat transfers coefficient of metal/mold interface for solidification radial values were much lower than those obtained under unidirectional flow in order that the effects of shrinkage of the metal in the case of radial solidification, is not compensated by increased contact between the metal and mold caused by the gravitational effect in the case of radial solidification;

The structural parameters studied were consistent with analytical model proposed by Santos (2006);

The Primary dendritic spacing grows at first, but with the evolution of solidification to a specific position suffers a reversal of behavior;

O Secondary dendrite spacing does not present a significant variation in length of the columnar zone, and;

The Comparison between the experimental results and those obtained using the numerical method show good agreement indicating the accuracy of the latter method.

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References

BOWER, T. F.; BRODY, H. D.; FLENINGS, M. C. Measurements of Solute Redistribution in Dendritic Solidification. **Transactions of AIME**, v. 236, n. 10, p. 624-634, 1966.

GARCIA, A. **Solidificação**: fundamentos e aplicações. Campinas: Unicamp, 2001.

GÜNDÜZ, M.; ÇADIRLI, E. Directional solidification of aluminium-copper alloys. **Materials Science and Engineering A**, v. 327, n. 2, p. 167-185, 2002.

MELO, M. L. N.; PENHALBER, C. L.; PEREIRA, N. H. A.; PELLICIARI, C. L.; SANTOS, C. A. Numerical and experimental analysis of microstructure formation during stainless steels solidification. **Journal of Materials Science**, v. 42, n. 7, p. 2267-2275, 2007.

MELO, M. L. N. M.; RIZZO, E. M. S.; SANTOS, R. G. Predicting dendrite arm spacing and their effect on microporosity formation in directionally solidified Al-Cu alloy. **Journal of Materials Science**, v. 40, n. 7, p. 1599-1609, 2005.

SANTOS, C. A.; QUARESMA, J. M. V.; GARCIA, A. Determination of transient interfacial heat transfer coefficients in chill mold castings. **Journal of Alloys and Compounds**, v. 319, n. 1-2, p. 174-186, 2001.

SANTOS, C. A.; SIQUEIRA, C. S.; GARCIA, A.; QUARESMA, M. V.; SPIM, J. A. Metal-Mold Heat transfer during horizontal and vertical unsteady-state solidification of Al-Cu and Sn-Pb alloys. **Inverse Problems in Science and Engineering**, v. 12, n. 3, p. 279-296, 2004.

SANTOS, R. G. **Transformação de fases em materiais metálicos**. Campinas: Unicamp, 2006.

SILVA, B. L.; GARCIA, A.; SPINELLI, J. E. The effects of microstructure and intermetallic phases of directionally solidified Al Fe alloys on microhardness. **Materials Letters**, v. 89, n. 15, p. 291-295, 2012.

SOUZA, E. N.; CHEUNG, N.; GARCIA, A. The correlation between thermal variables and secondary spacing during solidification of horizontal cylinders of Sn-Pb alloys. **Journal of Alloys and Compounds**, v. 399, n. 16, p. 110-117, 2005a.

SOUZA, E. N.; CHEUNG, N.; SANTOS, C. A.; GARCIA, A. Factors affecting solidification thermal variables along the cross section of horizontal cylindrical ingots. **Materials Science and Engineering. A, Structural Materials: properties, microstructure and processing**, v. 397, n. 25, p. 239-248, 2005b.

SPINELLI, J. E.; CHEUNG, N.; GOULART, P. R.; QUARESMA, J. M. V.; GARCIA, A. Design of mechanical properties of Al-alloys chill castings based on the metal/mold interfacial heat transfer coefficient. **International Journal of Thermal Sciences**, v. 51, n. 10, p. 145-154, 2012.

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