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Analysis of permeability of interdendritic channels during solidification of aluminum magnesium alloys

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Analysis and modelling

ABSTRACT

Purpose: The knowledge of the variation of permeability in interdendritic channels is important in order to analyze the ability of the liquid flow compensate the shrinkage of the alloy during solidification. In this work the influence of the magnesium content in the permeability of interdendritic channels during unidirectional solidification of Al-Mg alloys is analyzed.

Design/methodology/approach: Al-Mg alloys with 5, 10 and 15 wt% Mg were submitted to unidirectional solidification leading to a columnar dendritic structure. From the samples obtained, the primary and secondary dendrite arms spacing variations during the solidification process were measured. Applying a heuristic method, developed by some of the authors of this work, the variation of permeability of interdendritic channels for a flow parallel to primary dendrite arms was estimated as function of primary and secondary dendrite arms spacing, and liquid fraction variations during solidification.

Findings: From the results obtained for the three alloys with different compositions it was concluded that the behavior of the permeability depends on the relation between secondary and primary dendrite arms spacing and for the same distance from the metal/mould interface the permeability decreases when the magnesium content increase.

Research limitations/implications: The magnesium content affects the primary and secondary dendrite arms spacing affecting as consequence the permeability of the interdendritic channels. Both primary and secondary dendrite arm spacing increases with magnesium content. The permeability depends on primary and secondary dendrite arm spacing, but also on the relation between these parameters.

Originality/value: It was concluded that, for Al-Mg alloys, the permeability of interdendritic channels decreases as magnesium content increases, indicating that the probability of microporosity formation increases for greater magnesium content.

Keywords: Solidification; Permeability; Al-Mg alloys

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1. Introduction

In metallic alloys, which freeze over a range of temperature, the rejection of solute ahead of the solid/liquid interface leads to a dendritic growth of the solid phase throughout the liquid phase, and a mushy zone where solid and liquid coexist, characterized by a fine mesh of solid dendrites interdendritic channels filled with liquid metal, is created. A flow of liquid metal in the interdendritic channels during solidification is necessary to compensate the shrinkage of the metallic alloy in order to avoid microporosity formation. As the dendritic structure is characterized by tortuous ramified solid branches, a pressure drop in the liquid flow between the entrance and the bottom of these channels is observed. This liquid flow in the fine mesh of interdendritic channels can be treated as a flow through a finely porous media and the Darcy's law can be applied to estimate the pressure drop in the channels [2]. To apply the Darcy's law it is necessary to know the permeability of the interdendritic channels which depends on the liquid fraction and the primary and secondary dendrite arms spacing. These parameters vary during the solidification, leading to a variation of the permeability [8].

The first measurement of permeability in interdentritic channels was carried out by Piwonka and Flemings [11] forcing liquid lead throughout solidifying Al-4.5 wt pct Cu. Later some other works have been reported experimental measures of permeability of metallic alloys in different conditions. Among these Apelian et al. [1] measured the permeability of Al-Si alloys using water as fluid, Streat and Weinberg [13] measured interdendritic flow rate in a Pb-20 wt% Sn alloy using a Pb-Sn alloy as fluid, Nasser-Rafi et al. [6] analyzed the permeability of directionally solidified Pb-20 wt% Sn alloy, for different primary and secondary dendrite arms spacing, considering both liquid flow parallel and normal to primary dendrite arm and Murakami et al. [4,5] carried out measurements of permeability using directionally frozen borneol-paraffin organic alloy and aqueous solution as fluid. Permeability was measured for different primary and secondary dendrite arms spacing and liquid fractions for flow parallel and normal to primary dendrite arm. Poirier and Ganesan [9] measured permeability of Al-15.6 wt pct Cu with equiaxial structure using the eutectic Al-Cu as fluid, analyzing the influence of the coarsening and. Poirier and Okansey [10] measured the permeability for flow through equiaxial mushy zone of a Pb-Sn alloy, varying the liquid fraction. Recently two of the authors of the present work proposed heuristic relations to estimate the tortuosity of interdendritic channels in columnar dendritic mushy zone, for flow parallel and normal to primary dendrite arms, as function of the relation between secondary and primary dendrite arms spacing and liquid fraction [3]. These relations, introduced in equations derived from Darcy and Hagen Poiseuille laws, permitted to obtain equations to correlate the permeability of the interdendritic channels with primary and secondary dendrite arms spacing and liquid fraction. Results obtained applying the equations obtained presented good fit as compared with experimental results obtained by different authors. The model was also applied by the authors to predict numerically microporosity formation during solidification of Al-4.5 wt% alloy [12]. In this work, applying these relations, the influence of the magnesium content in the permeability of interdendritic channels during unidirectional solidification of Al-Mg alloys with 5, 10 and 15 wt% Mg was analyzed. From the samples with columnar dendritic structure obtained experimentally, the primary and secondary dendrite arms spacing variations during the solidification process were measured and permitted to estimate the variation of permeability of interdendritic channels for a flow parallel to primary dendrite.

2. Materials and methods

The three Al-Mg alloys containing 5, 10 and 15 wt% Mg were prepared and were directionally solidified using a experimental device showed schematically in Figure 1. The alloys were melted and poured in a cylindrical ceramic holder tube with a internal diameter of 60 mm and 260 mm in length positioned over a water cooled cooper mould kept at 550°C. A superheat of about 10% was adopted in all experiences, which mean initial temperatures equal to 650, 670 and 700°C for the alloys with 5, 10 and 15% Mg, respectively. Argon was injected in the melt before pouring to eliminate dissolved gases.

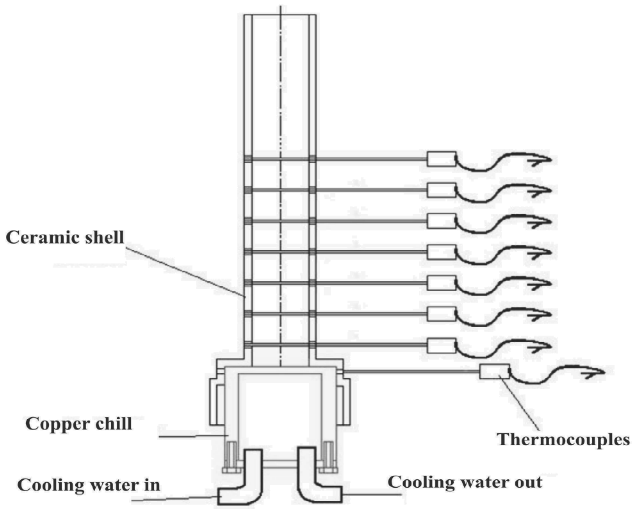

Fig. 1. Schematic representation of the experimental device used to promote unidirectional solidification

The macro and microstructures were analyzed through optical microscopy. The longitudinal sections of the solidified specimens were polished and etched for macroscopic examination. The Al-Mg alloys were etched with a reagent containing 20 ml glycerin, 30 ml HCl, 2 ml saturated water solution $FeCl_3$, 1ml HNO_3 and HF (7 drops). Selected samples of the longitudinal sections were polished and etched for microscopic examinations. The alloy containing 5% wt% Mg was etched with a reagent containing 20 ml H_2O, 1ml HF, 6 ml HNO and 12 ml HCl and the alloys containing 10 and 15 wt% Mg with a 10% HF water solution. Dendrites spacing were measured using image processing system Neophot 32 (Carl Zeiss, Esslingen, Germany) and Leica Quantimet 500 MC (Leica Imaging systems Ltd., Cambridge, England).

3. Model description

The model applied to estimate de permeability is detailed in a previous work [3] and will be just briefly described in this work, for a liquid flow parallel to primary dendrite arms as showed in Figure 2.

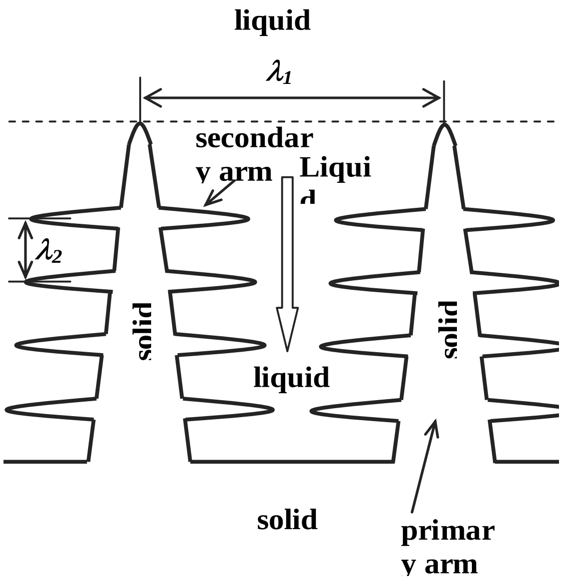

Fig. 2. Interdendritic channels in columnar dendritic mushy zone showing a liquid flow parallel to primary dendrite arms

From the Darcy's law for flow in a channel and From Haggen-Poiseuille's law (equations 1 and 2, respectively) [2,7]:

$$Q = K \cdot A \cdot \frac{\Delta P}{\mu \cdot L} \qquad (1)$$

$$Q = \frac{n \cdot \pi \cdot r^4}{8 \cdot \mu} \cdot \frac{\Delta P}{L \cdot \tau} \qquad (2)$$

where Q is the volume flow rate, K is the permeability of the channel, A is the cross sectional area, ΔP is the pressure drop in the channel, μ is the viscosity of the liquid, L is the length of the channel, n is the number of channels per unity area, r is the radius of the channel and τ is the tortuosity factor of the channel, which takes into account the fact that the channels are not straight and smooth, and an effective length (Le) of the channel is defined by:

$$L_e = L \cdot \tau \qquad (3)$$

and considering that the volume fraction of the liquid (f) is given by:

$$f = \frac{n \cdot \pi \cdot r^2 \cdot L_e}{A.L} \qquad (4)$$

the following equation is obtained for a liquid flow parallel to primary dendrite arms (see Figure 2):

$$K_p = \frac{f^2 \cdot \lambda_1^2}{8 \cdot \pi \cdot \tau^3} \qquad (5)$$

where λ1 and λ2 are, respectively, primary and secondary dendrite arm spacing. From the model proposed [12], for a flow parallel to primary arms the tortuosity is given by:

$$\tau = 1 + \left(\frac{\lambda_2}{\lambda_1}\right) + \left(\frac{\lambda_2}{\lambda_1}\right)^f + \left(\frac{\lambda_2}{\lambda_1}\right)^{f^2} + \left(\frac{\lambda_2}{\lambda_1}\right)^{f^3} \qquad (6)$$

4. Results and discussion

From the macrographies obtained, the extension of the columnar zone was measured for each composition analyzed. Figure 3 shows the extension of columnar zone as function of magnesium content. It is observed that the extension of columnar zone decreases and varies linearly with the magnesium content. The permeability was determined in the extension of the columnar zone for the Al-Mg alloys containing 5, 10 and 15 wt% magnesium.

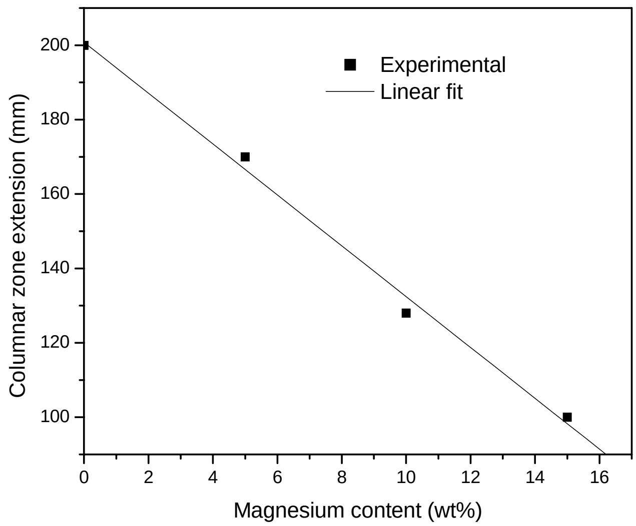

Fig. 3. Extension of columnar zone as function of magnesium content

From experimental measurements obtained for primary and secondary dendrite arm spacing during the solidification of the

Al-Mg alloys containing 5, 10 and 15 wt% magnesium the variation of these parameters during the solidification processes was analyzed. Figures 4 and 5 presents, respectively for primary ($\lambda 1$) and secondary ($\lambda 2$) spacing, the variation of the spacing with the distance (x) from metal/mold interface, for the three alloys studied. In Figure 4 it is observed that primary dendrite arm spacing increases during the solidification processes as heat transfer coefficient at metal/mould interface decreases, due to the formation of an air gap at metal/mold interface as consequence of alloy shrinkage, and thermal resistance of increasing solidified shell increases. The results presented in Figure 4 also indicate that for Al-Mg alloys the primary spacing increases with magnesium content. In Figure 5 it is observed that secondary dendrite arm spacing also increases with the distance from interface, for the same reasons, and that this spacing increases with magnesium content. The lines in the figures represent the best fit of experimental measurements expressing the dependence between spacing and position as a power function.

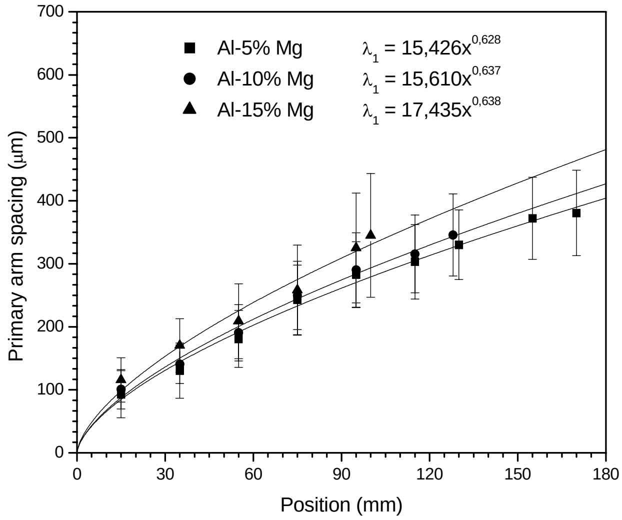

Fig. 4. Variation of primary dendrite arm spacing as function of the distance from metal/mold interface during solidification of Al-Mg alloys containing 5, 10 and 15 wt% magnesium

As the permeability of interdendritic channels depends on dendrite arms spacing, it will vary during the solidification processes and with the magnesium content.

Applying the equations 5 and 6 and adopting the experimental measurements of primary and secondary dendrite arms spacing the variations of the permeability of the interdendritic channels in the columnar zone during unidirectional solidification of the Al-Mg alloys were determined. The variation of permeability (K) was calculated as function of liquid fraction (f), see equations 5 and 6, in different positions of the solidifying alloy.

Figure 6 shows, for the alloy Al 5 wt% Mg, the variation of permeability of interdendritic channels as function of liquid fraction at different distances from metal/mold interface. This alloy presents the greater extension of columnar zone, as it is observed in Figure 3. From the results is clear that permeability increases as the distance from metal/mold interface increases, as consequence of the strong influence of primary dendrite arm spacing (see equation 5). It is observed that permeability reaches an approximately constant value for distances far from metal/mold interface. The results show that permeability of interdendritic channels is practically negligible for liquid fractions smaller than 0.5. Figures 7 and 8 presents the variation of permeability for the alloys Al 10 wt% Mg and Al 15 wt% Mg. The same behavior is observed in these cases but the extension of columnar, in which the permeability is determined, decreases as magnesium content increases.

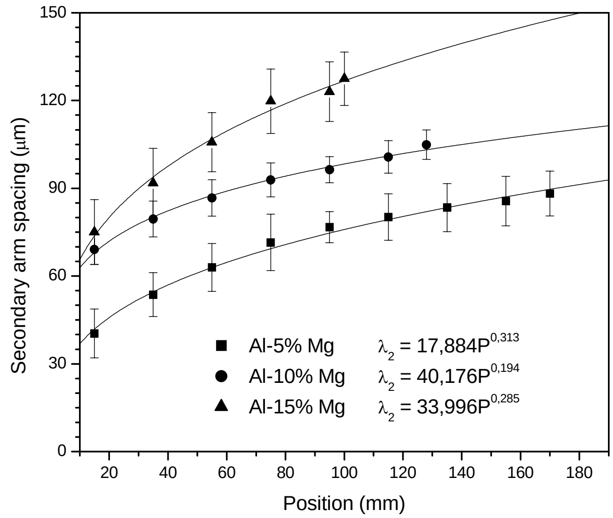

Fig. 5. Variation of secondary dendrite arm spacing as function of the distance from metal/mold interface during solidification of Al-Mg alloys containing 5, 10 and 15 wt% magnesium

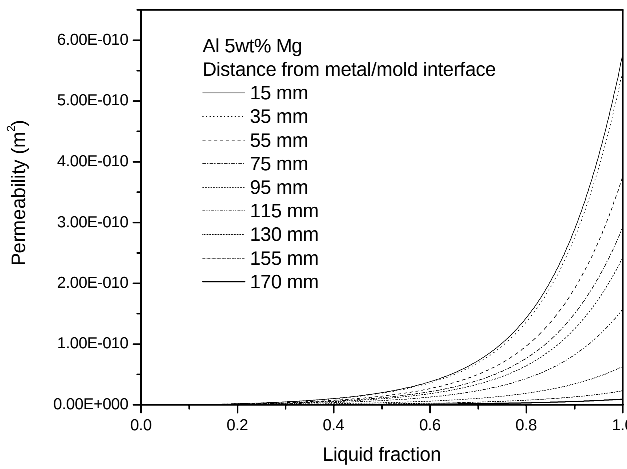

Fig. 6. Variation of permeability of interdendritic channels as function of liquid fraction at different distances from metal/mold interface for the alloy Al 5 wt% Mg

Comparing the results for permeability of interdendritic channels for the different magnesium content it is observed that for a same distance from metal/mold interface the permeability decreases as the magnesium content increases. As it was related by Santos and Melo [3] the permeability decreases as the relation between secondary and primary dendrite arms spacing increases. From the results presented in Figures 4 and 5 this relation can be determined for the alloys analyzed and it is observed that in fact the relation between secondary and primary arms spacing increases as the magnesium content increases, decreasing the permeability.

As the permeability is associated to the facility of liquid flow in interdendritic channels, the possibility of microporosity formation increases as the permeability decreases and, for this reason, increases as magnesium content increases.

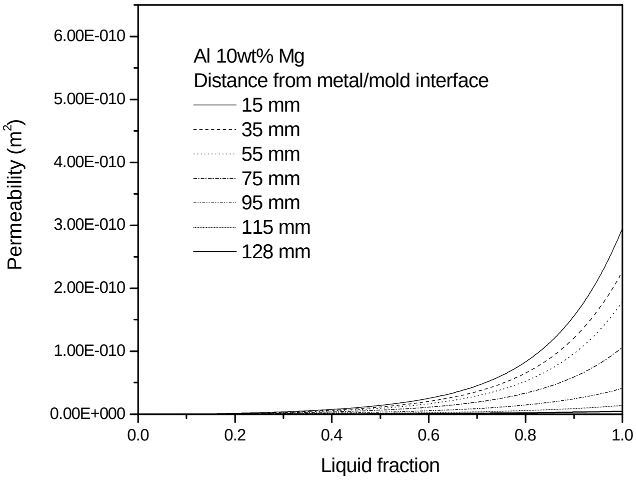

Fig. 7. Variation of permeability of interdendritic channels as function of liquid fraction at different distances from metal/mold interface for the alloy Al 10 wt% Mg

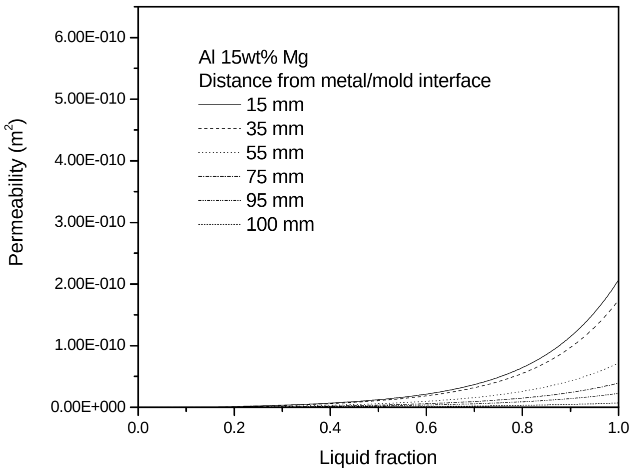

Fig. 8. Variation of permeability of interdendritic channels as function of liquid fraction at different distances from metal/mold interface for the alloy Al 15 wt% Mg

5. Conclusions

Applying the experimental results obtained in this work for primary and secondary dendrite arms spacing and the equations 5 and 6, the variation of permeability of interdendritic channels at different distances from metal/mold interface was determined for the Al-Mg alloys with 5, 10 and 15 wt% Mg. The results permitted to conclude that the magnesium content affects the primary and secondary dendrite arms spacing affecting as consequence the permeability of the interdendritic channels. The results show that both primary and secondary dendrite arm spacing increases with magnesium content. The permeability depends on primary and secondary dendrite arm spacing, but also on the relation between these parameters. From the results it was concluded that, for Al-Mg alloys, the permeability of interdendritic channels decreases as magnesium content increases, indicating that the probability of microporosity formation increases for greater magnesium content.

Acknowledgements

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