Prediction of porosity contents and examination of porosity formation in Al–4.4%Mg DC slab

Hiromi Nagaumi*

Research and Development Center, Structure Analysis and Systems Design Division, Nippon Light Metal Company Ltd., 1-34-1 Kambara, Kambara-cho, Ibana-gun, Shizuoka-ken 421-3291, Japan

Received 15 June 1999

Abstract

A new method for predicting porosity contents in Al–4.4% Mg DC sheet ingot (slab) is proposed. Hydrogen supersaturated mass in the inter-dendritic liquid and the pressure drop were taken into account for the porosity prediction. Using the method, the porosity contents were calculated and they well agreed with the experimental results. Thus it becomes possible to predict the porosity contents in the slab quantitatively. Furthermore, the porosity generation mechanism was observed from the surface to the center in the slab. The quantities and area fractions of the porosity were measured quantitatively by using an image analysis apparatus (Lazex). An explanation of this kind of porosity generation mechanism and the distribution of the porosity was attempted by using a local equivalent pressure and hydrogen supersaturation in dendritic solidification. The effects of parameters such as thermal gradient and cooling rate on the porosity contents were investigated analytically and the distribution of porosity and porosity contents in the slab of Al–4.4% Mg alloys were determined.

© 2001 Elsevier Science Ltd. All rights reserved.

Keywords: DC sheet ingot; Al–Mg alloy; Porosity contents; Porosity distribution; Pressure drop

1. Introduction

In general, porosity defects in aluminum alloys are caused by hydrogen gas and solidification contraction. Investigations on porosity defects have been reported in many previous studies [1–9]. Recently, many prediction methods of porosity formation have been proposed using computer simulation. These predicting methods can mainly be divided into two kinds, one being used to predict the occurrence of porosity [2,10–12], the other being used to predict the porosity content and porosity size [13–18]. The former kind was proposed by Niyama using the thermal gradient method [2] for application to shrinkage prediction in steel casting, and by Lee using the LCC method [12] for application to an Al–7Si–0.3Mg alloys casting. The latter kind was proposed by Kubo [13] who took the gas evolution and inter-dendritic flow into consideration, and applied it to Al–4.5Cu and Cu-8% alloy castings. These researches are mainly done for sand casting and die casting. Although there are many application instances in casting, these models are not suitable for applying to DC casting, because the cooling rate and thermal gradient are much larger than for sand casting or die casting. Studies on the porosity defects in the DC casting just have been reported by Nagaumi et al. [19]. In this study, a new predicting method has been developed for predicting the porosity in a slab of Al–4.4%Mg alloy. The model considers both hydrogen supersaturation in the inter-dendritic liquid and local equivalent pressure. Using the method, the porosity contents were calculated and agreed well with the experimental results. Furthermore, an explanation of this kind of porosity generation mechanism and distribution of the pore was attempted by using a local equivalent pressure and hydrogen supersaturation during dendritic solidification. The effects of solidification parameters on porosity formation were investigated analytically and the distribution of porosity and porosity content in the slab of Al–4.4%Mg alloy were clarified.

2. Experimental procedure

Slabs of Al–4.4%Mg alloy with cross-sectional dimensions of 406 mm thickness and 1110 mm width, were cast by typical DC under the following conditions: casting temperature 1003 K; casting speed 58 mm/min; metal level 33 mm; water supply 410 l/min.
where the equivalent diameters were more than $\Phi 6 \mu m$ were measured and the porosity fraction was defined as the average value of the porosity area that was measured at one location, $n = 10$. The porosity volume fractions were measured by the precision density method (Archimedes’ principle), and the hydrogen contents in the slab were determined from the surface to the center using the Ransley method, which is one of the standard methods for obtaining accurate analysis of the hydrogen content in a metal. Dendrite arm spacing (DAS) was measured on pictures of 100 times magnification by the secondary dendrite spacing arm method.

3. Analysis method

3.1. Solidification analysis

A two-dimensional thermal model without fluid flow which was taken in the longitudinal section with a casting length of 1000 mm from the bottom, was used for calculation, as shown in Fig. 2. The center line of the slab was assumed to have a geometry and thermal boundary that which was symmetrical. The calculation range consisted of metal, mold and bottom. An unsteady-state thermal conduction analysis was carried out for the casting process using the direction-finite-difference method. The enthalpy method was used to account for the latent heat during solidification, and the relation between the solid fraction and the temperature was calculated by the curve of specific heat which was continuously measured during solidification. The physical properties used in the calculation are shown in Table 1.

Fig. 1. Schematic diagram of the experimental apparatus.

Fig. 2. Simulation model.
3.2. Porosity calculation

Porosity is considered to form not only by pressure drop, but also as a result of gas rejection into the inter-dendritic liquid during solidification. According to the postulation of Kao [15], the porosity content can be simplified to

\[ V_p(\%) = \frac{dRT\rho}{MP^*} \]  \hspace{1cm} (1)

where \( \phi \) is the supersaturated hydrogen content in the liquid, \( R \) the gas constant, \( M \) the molecular weight of the gas phase, \( T \) the temperature, \( \rho \) the density at the final stage of solidification and \( P^* \) is the local equivalent pressure, where the local equivalent pressure is defined as the sum of pressure drop (\( \Delta P \)) due to shrinkage during interdendritic flow, atmospheric pressure (\( P_0 \)), static pressure (\( \rho gh \)) and pressure due to surface tension (\( P_s \)). \( P^* \) can be expressed as the following:

\[ P^* = P_0 + \rho gh - \Delta P + \frac{2\sigma}{R_p}. \] \hspace{1cm} (2)

However, the atmospheric pressure and the static pressure are considered as constant at a fixed level, so it is the pressure due to shrinkage and surface tension that are to be discussed. The calculation methods of these two pressures can be described as follows.

3.2.1. Pressure drop due to shrinkage

In this development, solidification direction was supposed to change along the normal direction of a sump during the steady stage of DC slab. Pressure drop due to shrinkage during interdendritic flow can be expressed by the following equations [19]:

\[ \Delta P_x = \frac{\beta\mu\Delta T}{3.75 \times 10^{-4}f_1d_2} \times \frac{V_s}{G} \cos^2\alpha, \] \hspace{1cm} (3)

\[ \Delta P_y = \frac{\beta\mu\Delta T}{3.75 \times 10^{-4}f_1d_2} \times \frac{V_s}{G} \sin^2\alpha - \rho_s g \frac{\Delta T}{G} \sin\alpha, \] \hspace{1cm} (4)

where \( V_s \) is solidus velocity, \( \mu \) the viscosity of the interdendritic liquid, \( f_1 \) the volume fraction of the interdendritic liquid, \( \Delta T \) the solidification range, \( \beta \) the solidification shrinkage, \( G \) the thermal gradient, \( d_2 \) the DAS, \( K \) the permeability of the solid–liquid zone, \( g \) the gravitational acceleration, and \( \alpha \) is an angle between the normal direction of sump and \( x \) axial. Then the pressure drop is

\[ \Delta P = \sqrt{\Delta P_x^2 + \Delta P_y^2}. \] \hspace{1cm} (5)

3.2.2. Pressure due to surface tension

Generally, the pressure due to surface tension can be expressed as

\[ P_s = 2\sigma/R_p, \] \hspace{1cm} (6)

where \( \sigma \) is the surface tension of the interdendritic liquid, and \( R_p \) is the radius of curvature of the porosity.

The surface tension of Al–Mg alloys can be calculated using Jacques’ approximate equation [20]. In this development, the surface tension of Al–4.4%Mg alloy is 920 N/m. Generally in dendritic solidification, the radius of curvature of a pore is assumed to be equal to the DAS/2 in casting. However, the size of the pores becomes very small because the cooling rate and the thermal gradient are large for DC casting as compared to sand casting and die casting. Consequently, it is considered that the supposed porosity size being equal to DAS is not realistic. In this study, the radius of curvature of the porosity is obtained by dividing the area of the pores into the Max diameter of the pores. An example of the measurement of pores is shown in Fig. 3. The distributions of the radius of pores and DAS in the slab are shown in Fig. 4. DAS and radius of pores decrease from the surface, after that they increase to 170 mm, then decrease to the center of the slab. As shown in Fig. 4, the distribution of the radius of pores correspond with the DAS. In other words, the bigger is the DAS at some point within the slab, the larger is the radius of the pores at the same location.

Then the relationship of the radius of curvature of the pores and DAS was obtained by using the regression method. Hence, the relation can be expressed as

\[ D_p = 2R_p = 0.2762\text{DAS} - 4.2, \] \hspace{1cm} (7)

where \( D_p \) is the equivalent diameter of pores.

3.2.3. The hydrogen supersaturated mass in the liquid

The contents of gas and hydrogen dissolved in a slab were determined from the surface to the center using the Ransely method as shown in Fig. 5. More than 95% gas contents are hydrogen gas in the slab and the hydrogen gas contents are almost steady from the surface to the center in the most part.
Fig. 3. An example of porosity measurement using Luzex.

Fig. 4. Distribution of DAS and porosity size in the slab.

Fig. 5. Distribution of hydrogen gas in the slab.

Thus it is considered that the hydrogen gas is the only gas which dissolved in the slab.

Before the formation of porosity, the partition of hydrogen between solid and liquid can be described by the Brody–Flemings equation as indicated by Fang and Granger [14]. In this case, assuming complete equilibrium, the distribution of hydrogen in liquid and solid phases can be expressed as

$$H_i = \frac{H_0}{(1 - (1 - k)f_s)},$$

(8)

$$H_s = k H_i,$$

where $K$ is the equilibrium partition coefficient, $H_0$ the
initial hydrogen content in the liquid, and $H_l$ and $H_s$ are the hydrogen contents in the liquid and solid phases, respectively.

The hydrogen solubility in the liquid is given by Sievert’s law according to

$$H_d = K_H \sqrt{P},$$  \hspace{1cm} (9)

where $K_H$ is the Sievert’s constant in the liquid, $P$' the local equivalent pressure. The hydrogen supersaturated mass in the interdendritic liquid is defined as

$$\phi = H_l - H_d.$$  \hspace{1cm} (10)

4. Analytical results and examination

4.1. Experiment results

Fig. 6 shows an observation of porosity features from the surface to the center of the slab. The sizes of pores become very small near the surface of the slab (from surface to 60 mm). In the surface layer, the pores exist mostly between secondary dendrite arms as long ellipses, because they are restrained by the growth of dendrite arms. The sizes of pore in the middle layer (from 80 to 140 mm) become large and the fractions of porosity increases greatly. It is observed that most of the pores exist between secondary dendrite arms, with a small part distributed along the grain boundary. In the center layer, the sizes of pores will increase and exist not only between secondary dendrite arms but also between the primary dendrite arm where the shapes of porosity are irregular and show typical shrinkage pores.

The distribution of amount per unit and average fractions of pores that were measured are shown in Fig. 7. The distribution of pores corresponds to the fraction from the surface to the center, and both increase to 180 mm; after that they decrease up to the center. The fraction is extremely small in the surface layer: less than approximately 0.1%. The minimum fraction is 0.038% at 20 mm from the surface. The fraction increases gradually from 60 until 120 mm: after that, the fraction rapidly increases and reaches the maximum of about 1.0% at 180 mm.

Fig. 7. Distribution of amounts and average fraction of area of porosity in the slab.

Fig. 8. Comparison of calculated and measured temperature as a function of time.

Fig. 6. Observation of porosity features from the surface to the center in the slab.
4.2. Calculated results

Fig. 8 shows the comparison of calculated and measured temperature from the surface to the center of a slab. The appropriateness of this analysis models was confirmed because the calculated values agree with the experimental results, as shown in Fig. 8.

Fig. 9 indicates the change in the cooling rate and thermal gradient in the slab. The cooling rate increases from surface to 20 mm and reaches the maximum value at 20 mm, then it rapidly decreases to 160 mm and reaches the minimum value at 160 mm. After that it increases slowly up to the center. The thermal gradient has the same tendency as the cooling rate.

Fig. 10 shows the comparison between distribution of calculated DAS and measured ones from the surface to the center. The calculated values correspond well with the experimental results, as shown in Fig. 10, both minimum values being at 20 mm from the surface. The minimum DAS is 32.6 μm in experiments and 28.5 μm in the calculation. Then, they increase from 20 to about 170 μm, and become maximum at 175 (for experiments) and 160 μm (for calculation). In the experiments, the maximum DAS reached 58.3 and 54.5 μm by the calculation, respectively. Then the DAS decreases again up to the center.

Fig. 11 indicates the change in the local equivalent pressure and solidus velocity in a slab. The pressure from the surface decreases after that it increases to 30 mm and reaches the maximum value at 30 mm, then decreases to 180 mm and reaches the minimum value. Finally, it increases from 180 mm to the center again. The change in the local equivalent pressure corresponds with the cooling rate and thermal gradient. The solidus velocity increases from the surface to 20 mm, after which it decreases to 140 mm, then suddenly increases to the center.

Fig. 12 shows the distribution of the hydrogen supersaturated mass in the slab by Eq. (10). The hydrogen supersaturated mass increase with decreasing equilibrium hydrogen content in the liquid as shown in Eq. (10). As the local equivalent pressure becomes small, the hydrogen supersaturated mass increase because the equilibrium hydrogen content in the liquid is in proportion to the local equivalent pressure. The distribution of the hydrogen supersaturated mass in the slab has the same general distribution as the DAS.
Comparison of calculated porosity content and measured ones from the surface to the center in the slab is shown in Fig. 13. The calculated results agree well with the experimental ones except for near to the surface (until 20 mm from the surface). The porosity content appears to increase from 20 to about 180 mm, because the local equivalent pressure goes down and the hydrogen supersaturated mass in the liquid increases. In the experiments, the maximum porosity content reached about 0.4% at 175 mm, whilst in the calculations it reached 0.37% at 180 mm. From 180 mm to the center of slab, the porosity contents decrease again.

4.3. Porosity formation mechanism

According to the postulation of Kubo and Pehlke [13] and the experimental results of Kao [15], pores nucleate easily at the root of dendrite cells. The nuclei grow as the decrease in pressure and the increase in hydrogen content in the liquid, and finally they form three kinds of pores as shown in Fig. 14. The porosity nucleus grows slowly, because there are few pressure drops and hydrogen supersaturation in the inter-dendritic liquid with a solidification process as shown in the surface layer, and then they become elongated pores, because they are restrained by the growth of the dendrite spacing arms as shown in Fig. 11(b1). Experimental results show that the pores are usually long and narrow.

As solidification progresses, the pores can detach from the dendrite by buoyant and connective forces as shown in Fig. 11(b2), and there are more pressure drops and more hydrogen supersaturation in the middle layer of the slab, so the pores become larger than those in the surface layer. Furthermore, in the center layer the neighboring dendrites collide because the pressure drop is dramatic and the solidification velocity greatly increases, thus inter-dendritic feeding becomes difficult at the later stage of solidification. At that point, the porosity is assumed to grow to compensate for solidification shrinkage. This is called shrinkage porosity.

4.4. Effect of solidification parameters on porosity

The effects of the thermal gradient on the porosity content is shown in Fig. 15. In this figure, the porosity content decreases with increasing the thermal gradient, but when the thermal gradient is higher than 5000 K/m, the porosity content is found to be almost invariant. As the value of the thermal gradient is less than 2500 K/m, the porosity content rapidly increases.

Fig. 16 shows the relationship between porosity content
and the cooling rate. As the cooling rate becomes fast, the porosity content decreases. When the value of the cooling rate is larger than 5.0 K/s, the porosity content will decrease no further with the increase of the cooling rate. When the cooling rate is less than 1.0 K/s, the porosity content is found to increase rapidly.

The effect of DAS on the porosity content is shown in Fig. 17. The porosity content is linear in proportion to DAS and when DAS becomes coarse the porosity content becomes large. Because DAS is directly proportional to the radius of curvature of the porosity when the radius of curvature of the porosity becomes large, the pressure due to surface tension becomes small, so that the porosity content increases.

5. Conclusions

In this study, porosity generation behavior was discussed from the surface to the center in a DC slab of Al–4.4%Mg alloy, and a new method for predicting the porosity content of Al–4.4%Mg slab was proposed. Porosity forms not only because of the pressure drop, but also as a result of hydrogen supersaturated mass in the liquid. Using the predicting method, the effects of solidification parameters such as the thermal gradient, cooling rate, and DAS were analytically investigated for the porosity content. The results of the analysis and experiments are given as follows:

1. Porosity forms when hydrogen gas is rejected into the liquid as a result of gas content supersaturation, and when the inter-dendritic liquid at the location becomes too difficult to flow into the local area to compensate for the solidification contraction caused by the local equivalent pressure, and the external pressure acting on a gas nucleus is less than the inner pressure.

2. The porosity sizes and the fractions increase from surface to 180 mm, then they decrease up to the center of the slab.

3. Minute pores are dominant in the surface layer, because there are few losses of pressure there. These pores became elongated, because they are restrained by the growth of the dendrite spacing arms and exist mostly in secondary dendrite spacing arms.

4. In the middle layer, the sizes of pore become large because the pressure drop increases greatly, and most pores exist in the secondary dendrite spacing arms, with a smaller part existing along the grain boundary.

5. In the center layer, neighboring dendrites collide because the pressure drop is dramatic and the solidification velocity becomes very great, so that inter-dendritic feeding becomes difficult at a later stage of solidification. At that point, the porosity is assumed to grow to compensate for solidification shrinkage. Pores appear as typical shrinkage pores.

6. The greater is the hydrogen supersaturated mass in the
liquid, and the lower the local equivalent pressure, the
greater the porosity content becomes.

7. The distribution of porosity content in the slab corre-
sponds to the distribution of DAS. As the DAS becomes
course the porosity content becomes large.

8. The porosity content decreases with increasing the
thermal gradient and cooling rate, but when the thermal
gradient and cooling rate are higher than 5000 K/m and
5.0 K/s, respectively, the porosity content is found to be
almost invariant.

References

[1] D.R. Irani, V. Kondic, Trans. AFS 77 (1969) 208.
[2] E. Niyama, T. Uchida, M. Morikawa, S. Saito, IMONO 54 (1982) 507.
[3] D.R. Poirier, K. Yeum, A.L. Maples, Metall. Trans. (1987) 1979.
[4] J.D. Zhu, I. Ohnaka, IMONO 59 (1987) 542.
[5] Q.T. Fang, P.N. Angalebechi, D.A. Granger, Light Metals (1988) 477.
[6] N. Roy, A.M. Samuel, F.H. Samuel, Metall. Mater. Trans. 27A (1996)
415.
[7] R. Fuoco, E.R. Correa, A.V.O. Correa, AFS Trans 103 (1995) 379.
[8] N. Roy, L. Zhang, P.R. Louchez, F.H. Samuel, J. Mater. Sci. 31
(1996) 1243.
[9] S. Shivkumar, D. Apelian, J. Zou, AFS Trans. 90–178 (1996) 897.
[10] I. Ohnaka, Y. Nagasaka, T. Fukasako, S. Oyama, IMONO 55 (1983)
758.
[11] I. Ohnaka, IMONO 61 (1981) 876.
[12] Y.E. Lee, E. Chang, C.F. Chieu, Metall. Trans. 21B (1993) 715.
[13] K. Kubo, R.D. Pehlke, Metall. Trans. 16B (1985) 359.
[14] Q.T. Fang, D.A. Granger, Light Metals (1989) 927.
[15] S.T. Kao, E. Chang, Y.W. Lee, MST 11 (1995) 933.
[16] J.D. Zhu, I. Ohnaka, IMONO 64 (1992) 19.
[17] G.K. Sigworth, C. Wang, Metall. Trans. 24B (1993) 349.
[18] T.W. Clyne, Metall. Trans. 13B (1982) 471.
[19] H. Nagaumi, K. Komatsu, M. Uematsu, J. Jpn. Inst. Light Metals 48-6
(1998) 269.
[20] E. Jacques, Schontens, J. Mater. Sci. 24 (1989) 2681.