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Shrinkage Porosity Criterion and Its Application to A 5.5 Ton Steel Ingot

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Abstract

In order to predict the distribution of shrinkage porosity in steel ingot efficiently and accurately, a criterion R√L and a method to obtain its threshold value were proposed. The criterion R√L was derived based on the solidification characteristics of steel ingot and pressure gradient in the mushy zone, in which the physical properties, the thermal parameters, the structure of the mushy zone and the secondary dendrite arm spacing were all taken into consideration. The threshold value of the criterion R√L was obtained with combination of numerical simulation of ingot solidification and total solidification shrinkage rate. Prediction of the shrinkage porosity in a 5.5 ton ingot of 2Cr13 steel with criterion R√L>0.21 $m\cdot{}^{\circ}C^{1/2}\cdot s^{-3/2}$ agreed well with the results of experimental sectioning. Based on this criterion, optimization of the ingot was carried out by decreasing the height-to-diameter ratio and increasing the taper, which successfully eliminated the centreline porosity and further proved the applicability of this criterion.

Keywords: Application of information technology to the foundry industry, Quality management, Shrinkage porosity, Ingot solidification, Numerical simulation

1. Introduction

As a raw material, the soundness of the steel ingot is of the utmost importance because its quality determines the quality of the product processed subsequently. In particular, shrinkage porosity is one kind of major defects which can cause the reduction of mechanical properties or structural unsoundness of the final products.

The inspection of shrinkage porosity in an ingot is difficult and expensive. However, with the development of the computer's technology, the prediction of shrinkage porosity in an ingot with the method of numerical simulation is becoming a fashion. Henzel et al.[1] and Niyama et al.[2] predicted the shrinkage porosity region in castings with the method of isotherm curve and temperature gradient separately. Niyama et al.[3] put forward $G/\sqrt{L}$ as prediction criteria based on a large amount of experiments and theoretical models. Where G is the temperature gradient and L is the cooling rate, both of which are evaluated at the end of solidification. The secondary dendrite arm spacing (SDAS) which has effect on the permeability in the mushy zone was not taken into consideration during the development of Niyama criteria. Lee et al.[4] put forward a new feeding efficiency parameter integrating all individual thermal variables, denoted as $(G\cdot t^{2/3})/R$, where t is local solidification time, and R is solidus velocity. This parameter is found satisfactory to predict the formation of porosity in Al-7Si-0.3Mg castings. Sigworth and Chengming Wang[5] developed a number of theoretical models to predict the formation of shrinkage porosity, while these models suggest a number of experiments. Carlson and Beckermann[6] put forward a dimensionless Niyama criterion to predict the presence and the quantity of shrinkage porosity that forms during solidification of metal alloy castings. Jiaqi Wang et al.[7]

compared the prediction of the centreline shrinkage porosity of a 100 t 30Cr2Ni4MoV ingot using several criteria and the experimental results, they found that $G/R^{0.5}$<2.5 ℃$s^{0.5}mm^{-1.5}$ was the best criterion.

In this paper, a new shrinkage porosity criterion $R\sqrt{L}$ is developed based on a theoretical model in which the thermal parameters and the dendrite structure are taken into consideration. A method to obtain the threshold value is put forward which combined the temperature evolution during the solidification of castings and the total solidification shrinkage rate of the alloy. The criterion $R\sqrt{L}>0.21$ m·°C$^{1/2}$·s$^{-3/2}$ was applied to the predict of the shrinkage porosity in a 5.5 ton ingot of 2Cr13 steel, and the results agreed well with the experimental ones observed by sectioning. Based on the criterion $R\sqrt{L}>0.21$ m·°C$^{1/2}$·s$^{-3/2}$, the designation of the 5.5 ton steel ingot was optimized to eliminate the centreline porosity successfully, which further proved the practical application of this criterion.

2. Shrinkage porosity criterion

2.1 Derivation of shrinkage porosity criterion

In the mushy zone, shrinkage porosity forms when the shrinkage can't be fed due to the bad flowing property of the liquid. Some researchers[8] regarded 0.3 as a critical liquid volume fraction of steel ingots at which the shrinkage porosity begins to form. However, the critical liquid volume fractions vary with the alloy being cast, the geometry of the castings and the cooling condition. Since the formation of shrinkage porosity has a strong relationship with the pressure drop in the mushy zone[9], we take the pressure gradient where liquid volume fraction is 0.3 in the mushy zone as the object of study. Obviously, a large pressure gradient implies the pressure reduces rapidly along the solidification direction, which promotes the formation of shrinkage porosity.

Assumptions are made as followings:

1) The flow of the liquid through the mushy zone obeys Darcy's law.
2) The liquid density (ρ_L) and solid density (ρ_s) are constant during solidification.

According to Darcy's law, the mean interdendritic flow velocity $\boldsymbol{v}$ in the mushy zone is linearly related to the pressure gradient as the following equation[9]:

$$v=-\frac{K}{\mu f_L}(\nabla P+\rho_L g) \qquad (1)$$

Where: K is a constant termed the permeability of the mushy zone, P is pressure, μ is viscosity, f_L is liquid volume fraction and g is acceleration due to gravity.

In general, the influence of gravity on the interdendritic flow velocity is insignificant, and this item can be neglected. The modulus of pressure gradient (hereafter referred to as pressure gradient) can be expressed as:

$$|\nabla P|=\frac{\mu f_L v}{K} \qquad (2)$$

The interdendritic flow velocity where f_L is 0.3 is related to the isotherm velocity[3] R where f_L is 0.3 and the total solidification shrinkage rate β which is defined as $\beta=(\rho_s-\rho_L)/\rho_L$. That is,

$$v=\beta R \qquad (3)$$

The permeability K depends on pore size and the structure in the mushy zone[10, 11], which can be written as

$$K=\gamma\lambda f_L{}^2 \qquad (4)$$

Where γ is a constant which depends on dendrite structure, λ is SDAS.

From equation(2) to equation(4), we obtain

$$|\nabla P|=\frac{\mu\beta}{\gamma f_L}\cdot\frac{R}{\lambda} \qquad (5)$$

The SDAS depends on cooling rate[12, 13] and can be expressed as $\lambda=aL^{-1/2}$,where a is a material constant. Therefore,

$$|\nabla P|=\frac{\mu\beta a}{\gamma f_L}\cdot R\sqrt{L} \qquad (6)$$

We denote $\frac{\mu\beta a}{\gamma f_L}$ as M, then equation (6) becomes

$$|\nabla P|=M\cdot R\sqrt{L} \qquad (7)$$

Since M is a material constant, the pressure gradient where liquid volume fraction is 0.3 depends on $R\sqrt{L}$. As mentioned above that a large pressure gradient promotes the formation of shrinkage porosity, $R\sqrt{L}$ can be regarded as a criterion which determines the formation of shrinkage porosity.

2.2 Threshold value of the criterion

Threshold value of $R\sqrt{L}$ above which shrinkage porosity forms in steel ingot varies with steel grade and size of ingot, so it's of great importance to determine threshold value of $R\sqrt{L}$. During solidification of steel ingot, the extent of feeding is different at different locations in ingot. Consequently value of $R\sqrt{L}$ differs with location in ingot. Using method of numerical simulation, values of $R\sqrt{L}$ at different locations in steel ingot can be obtained. Then integration of the volume whose values of $R\sqrt{L}$ are large can be carried out until the result is equal to the total solidification shrinkage rate. At this time, the corresponding value of $R\sqrt{L}$ can be regarded as threshold value of $R\sqrt{L}$. So, in order to obtain threshold value of $R\sqrt{L}$, a function *F(x)* is defined as following,

$$F(x)=\frac{1}{V_T}\cdot\sum V_i\left\{\left(R\sqrt{L}\right)_i\leq x\right\} \tag{8}$$

Where *F(x)* is the sum of the volume fraction of the volume cells where $R\sqrt{L}\leq x$ m·°C$^{1/2}$·s$^{-3/2}$ at f_L=0.3 during the solidification of an steel ingot, V_T is the total volume of the ingot, V_i is the volume of cell i, x is an argument which could be any positive value.

As a large value of $R\sqrt{L}$ promotes the formation of shrinkage porosity, the solution of equation(9) can be regarded as the threshold value of $R\sqrt{L}$.

$$F(x)=1-\beta \tag{9}$$

Namely, the shrinkage porosity criterion can be expressed as $R\sqrt{L}>x|_{F(x)=1-\beta}$.

For a certain steel ingot casting, the *F(x)-x* curve can be obtained with the help of numerical simulation of the solidification through which the thermal parameters where f_L is 0.3 can be got at any location of the ingot.

3. Experimental Procedure

3.1 Prediction of the shrinkage porosity in a 5.5 ton steel ingot

In order to check the accuracy of the shrinkage porosity criterion $R\sqrt{L}$, it's applied to the prediction of the shrinkage porosity in a 5.5 ton ingot of 2Cr13 steel as shown in Fig. 1. And the prediction results were compared with the experimental ones observed by sectioning.

The mould filling and solidification processes were performed by finite element method in ProCAST 2013.0 software. A three dimensional model was developed based on governing equations such as the Continuity equation, the Navier-Stokes equation, the Volume Fraction Equation, the Transport equations for the standard k-ε model, and Fourier's equation.

The metal-mould interface heat transfer coefficient varies with time [14, 15]. The heat transfer coefficients of both the metal-insulation brick interface and the mould-insulation brick interface were assigned as 30 W·m^{-2}·K^{-1}[16]. The heat transfer coefficient of hot top was calculated according to temperature measurement. The heat transfer coefficient of the air around mould wall was assigned according to the following equation (10) in which both radiation and convection heat transfer were taken into consideration [17].

$$h_{eff}=\varepsilon_{sm}\times\sigma\left(T_{sm}^2+T_e^2\right)\times\left(T_{sm}+T_e\right)+1.24\times\left(T_{sm}-T_e\right)^{0.33} \tag{10}$$

Where T_{sm} is the temperature around mould wall, T_e is the surrounding temperature, ε_{sm} is the heat emissivity coefficient which was assigned as 0.85, σ is the Stefan-Boltzmann constant. The initial temperature of the mould and insulation brick was assigned as 40 ℃. The composition of the ingot and the mould are shown in Table 1. Some properties of the molten steel were calculated with Scheil model. The thermal conductivity of the insulation brick was assigned as 0.29 W·m^{-1}·K^{-1} according to experiment[18].

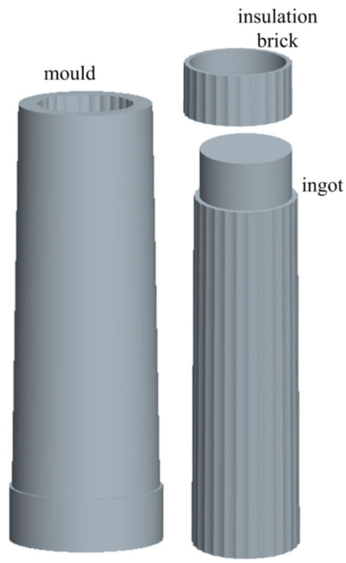

Fig. 1 The geometry of the 5.5 ton steel ingot and the mould

Table 1.
Composition of the ingot and the mould

materia	code	Composition (wt-%)					
		C	**Mn**	**Si**	**P**	**S**	**Cr**
melt	2Cr13	0.16÷0.25	0÷1	0÷1	≤0.04	≤0.03	12÷14
mould	iron	3.2÷3.8	0.8÷1.2	-	≤0.05	≤0.10	-

According the numerical simulation, the *F(x)-x* curve defined in equation(8) was obtained as shown in Fig. 2.

The ρ_s and ρ_L of 2Cr13 steel are 6883.1 kg/m^3 and 7245.4 kg/m^3 respectively, so, the total solidification shrinkage rate β is 0.05263. And then, 0.21 m·°C$^{1/2}$·s$^{-3/2}$ is obtained as the threshold value of $R\sqrt{L}$ with the combination of Fig. 2 and equation(9). Namely, $R\sqrt{L}>0.21$ m·°C$^{1/2}$·s$^{-3/2}$ is the shrinkage porosity criterion of the 5.5 ton 2Cr13 steel ingot.

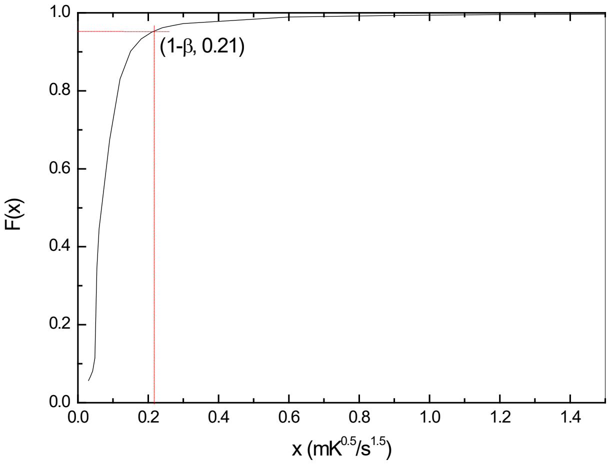

Fig. 2. $F(x)$-x curve of the 5.5 ton ingot of 2Cr13 steel

The predicted shrinkage porosity of the 5.5 ton ingot of 2Cr13 steel with the criterion $R\sqrt{L}$>0.21 m·°C$^{1/2}$·s$^{-3/2}$ is shown in Fig. 3 (a). Compared with the experimental sectioning of which the riser was cut off for some reasons shown in Fig. 3 (b), the predicted results are in good agreement with the experimental ones, which indicated the accuracy of the criterion $R\sqrt{L}$>0.21 m·°C$^{1/2}$·s$^{-3/2}$.

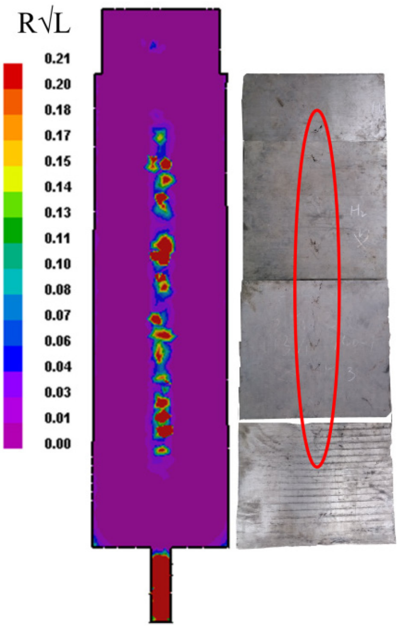

Fig. 3. Comparison of the predicted shrinkage porosity with the experimental sectioning, (a) the predicted, (b) the experimental

3.2 Optimization of the 5.5 ton ingot

In order to further prove the practical application of the criterion $R\sqrt{L}$>0.21 m·°C$^{1/2}$·s$^{-3/2}$, optimization of the 5.5 ton ingot of 2Cr13 steel was worked out to eliminate the centreline porosity based on this criterion.

Height-to-diameter ratio (H/D ratio) and taper of an ingot are main factors that have influences on solidification sequence and formation of shrinkage porosity[19-21]. A series of 5.5 ton ingots with different H/D ratios and taper were designed and whose shrinkage porosity were predicted with numerical simulation and the criterion $R\sqrt{L}$>0.21 m·°C$^{1/2}$·s$^{-3/2}$. Finally, an optimized design of the 5.5 ton ingot shown in Table 2 was obtained.

Table 2.
Geometric parameters of the preliminary and optimized design of the 5.5 ton ingot

Design	Height /mm	Top diameter/mm	Bottom diameter/mm	Taper	H/D ratio
preliminary	2520	630	660	1.19%	3.4
optimized	1613	826	786	-2.48%	1.7

The comparison of shrinkage porosity of the preliminary and optimized 5.5 ton ingot is shown in Fig. 4. It is obvious that the shrinkage porosity is almost eliminated. The melting and casting process of the optimized 5.5 ton ingot of 2Cr13 steel was conducted and the rolled products from the ingot passed the examination of ultrasonic inspection.

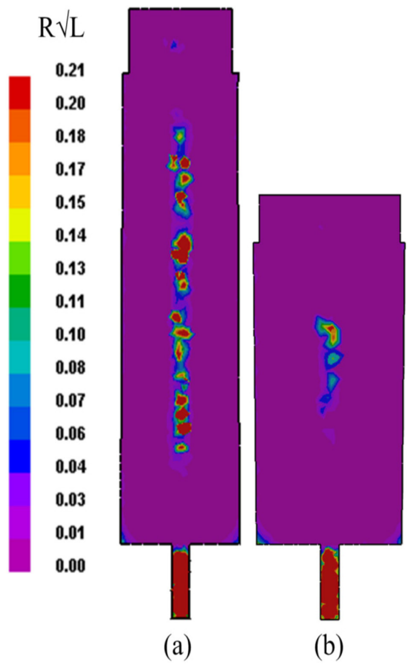

Fig. 4 Comparison of shrinkage porosity of the preliminary and optimized 5.5 ton ingot, (a) preliminary, (b) optimized

4. Discussion

The successful prediction of the distribution of shrinkage porosity with the criterion $R\sqrt{L}$ as shown in Fig. 3 demonstrates the applicability of the criterion. So far, most of the shrinkage porosity criterions were derived based on the pressure drop from the liquid to solid in the mushy zone[3, 5, 6]. Differently, in this paper the criterion $R\sqrt{L}$ was derived directly based on the pressure gradient where f_L=0.3 in the mushy zone instead of the pressure drop. This proves that the formation of shrinkage porosity is closely related to the pressure gradient in the mushy zone, and the pressure gradient at a low f_L can predict the formation of shrinkage porosity. A comparison of the predicted shrinkage porosity with the well-known Niyama criterion and $R\sqrt{L}$ respective is shown in Fig. 5. It can be seen that the predicted results of $R\sqrt{L}$ is as accurate as the ones of Niyama criterion. So, conclusions can be drawn that the formation of shrinkage porosity is not only related to the pressure drop but also to the pressure gradient in the mushy zone.

The influence of SDAS on the permeability is taken into consideration during the derivation of the criterion $R\sqrt{L}$, while the Niyama criterion doesn't concern it. From this point of view, the $R\sqrt{L}$ criterion has a more obvious physical meaning.

As the $R\sqrt{L}$ criterion is derived based on the assumption that the flow of the liquid through the mushy zone obeys Darcy's law, it can be used only to predict the shrinkage porosity forming during the stage of interdendritic feeding but not the pipe shrinkage in the top riser which forms during the stage of liquid feeding.

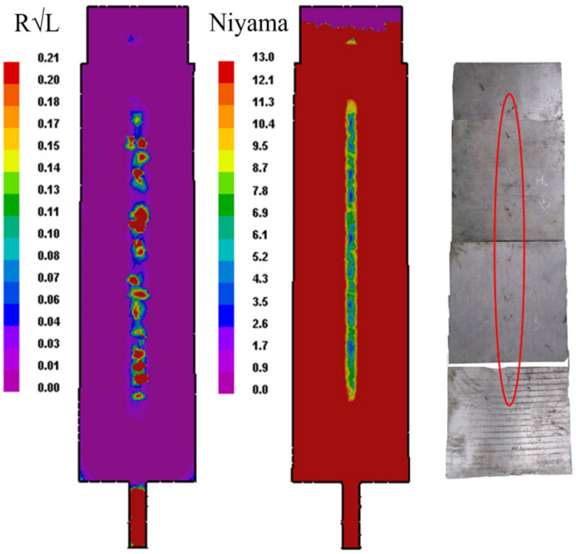

Fig. 5 Comparison of the predicted shrinkage porosity with the well-known Niyama criterion and $R\sqrt{L}$ respective, (a) $R\sqrt{L}$>0.21 criterion, (b) Niyama criterion, (c) experimental sectioning

Though the threshold value 0.21 $m\cdot{}^oC^{1/2}\cdot s^{-3/2}$ was obtained from the results of the numerical simulation of the preliminary 5.5 ton 2Cr13 ingot, it can be used in 5.5 ton 2Cr13 ingots of different designs. However, for other steel grades and weights of ingots the threshold values of criterion $R\sqrt{L}$ should be determined again with numerical simulation.

5. Conclusions

In order to control the shrinkage porosity in an ingot so as to improve metal yield and efficiency utilization of resources during foundry practice, shrinkage porosity criterion was investigated theoretically and practically.

1) A shrinkage porosity criterion $R\sqrt{L}$ which accounts for the solidification characteristics and the structure in the mushy zone was derived. And a method to obtain the threshold value of $R\sqrt{L}$ was put forward. The shrinkage porosity can be predicted accurately with the criterion $R\sqrt{L}$ and its threshold value.
2) The influence of SDAS on the permeability as well as the thermal parameters was taken into consideration during the derivation of the criterion $R\sqrt{L}$. Compared with the Niyama criterion, the physical meaning of the criterion $R\sqrt{L}$ is more reasonable.
3) The shrinkage porosity criterion $R\sqrt{L}$>0.21 $m\cdot ℃^{1/2}\cdot s^{-3/2}$ is applicable to 5.5 ton ingot of 2Cr13 steel with different H/D ratios and tapers.

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