Simulation of microstructures in solidification of aluminum twin-roll continuous casting

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Abstract

Based on the research on the solidification of twin-roll continuous casting aluminum thin strip, the analytical model of heterogeneous nucleation, the growth kinetics of tip (KGT) and columnar dendrite transformation to equiaxed dendrite (CET) of twin-roll continuous casting aluminum thin strip solidification are established by means of the principle of metal solidification. The foundation for the emulational simulation of twin-roll casting thin strip solidification structure is laid. Meanwhile has confirmed the mathematical simulation feasibility by using the Solidification Process of Twin-roll Continuous Casting aluminum Thin Strip.

1. Introduction

The twin-roll strip casting is regarded as the most prospective technology of near-net-shape casting. Twin-roll strip casting may save energy and manufacturing cost by eliminating some of the intermediate stages [1–5].

Previous investigations [3] indicated that the solidification structure of twin-roll thin strip, especially the crystal zone proportion, has obvious effect on the thin strip quality. The microstructures of thin strip depend on the casting process parameters, and microstructure has a great impact on its properties [6–7].

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In this study, a simple micro mathematical model was performed to simulate the solidification structure of twin-roll casting thin strip. Based on the micro mathematical model, the average grain size and the average columnar crystals deviation for twin-roll continuous casting aluminum thin strip is investigated and analyzed.

2. Micromodel

2.1. Nucleation model

Rappaz’s [8] continuous nucleation model is employed in the present investigation. Based on the following assumptions: (1) the fragmentation of dendrites and the oxidation of melt surface are neglected; (2) the effect of convection on nucleation is not considered. In the model, the density of grains, \( n(\Delta T) \), formed at any under cooling, \( \Delta T \), is given by

\[
n(\Delta T) = \frac{n_{\max}}{\sqrt{2\pi \Delta T_\sigma}} \exp\left( -\frac{1}{2} \left( \frac{\Delta T - \Delta T_N}{\Delta T_\sigma} \right)^2 \right) d(\Delta T)
\]

(1)

Where \( \Delta T_N \) is the mean nucleation under cooling; \( \Delta T_\sigma \) is the standard deviation and \( n_{\max} \) is the maximum density of nuclei.

2.2. Growth kinetics model

In general, the constrained dendrite tip growth during rapid solidification is described by the Kurz–Giovanola–Trivedi (KGT) model [9]. However, it is well known that the twin-roll thin strip casting is a near-rapid solidification process thus the dendrite growth rate is not very high, and the growth dynamics coefficient is very large. It was necessary to modify the model according to the solidification characteristics of twin-roll thin strip. The modified KGT model is given as

\[
\nu_{tip} = \alpha(\Delta T)^2 + \beta(\Delta T)^3
\]

(2)

Where \( \alpha \) and \( \beta \) are empirical constants.

2.3. Columnar to equiaxed transition (CET)

In general, after the molten metal is poured into the gap between the rolls, the nucleation will appear on the surface of rolls, and then much nucleus form. There will have internal nucleation when the columnar crystals front's liquid phase temperature achieves volume interior nucleation temperature \( T_i \). According to the theory proposed by Flood and Hunt [10], in afterward solidification process, the dendrite growth will transform from columnar to equiaxed growth. The CET model is given as

Center equiaxial crystal:

\[
f_s(t) \geq f_1
\]

(3)

Equiaxed-columnar crystals:

\[
f_2 < f_s(t) < f_1
\]

(4)

Columnar crystal:

\[
f_s(t) \leq f_2
\]

(5)
Where $f_1=0.49$, $f_2=0.0049$; $n(t)$ is the grain density at each time-step; $R_e(t)$ is the mean radius of equiaxed grain at each time-step; $f_i(t)$ is the internal solid fraction at each time-step, which can be expressed as: $f_i(t)=\Omega(t)$, where $\Omega(t)$ is the solutal supersaturation of dendrite tip at each time-step.

3. Validation of mathematical model

The aluminum thin strip was chosen to validate the mathematical model. The primary technical parameters of twin-roll caster are listed in Table 1. The thermo physical properties of aluminum needed for the model is listed in Table 2. The Simulated and experimental results of roll casting solidification microstructure at the casting speed of 2.0 m/min and under the conditions of pouring temperature being 695°C, melt pool height being 60 mm are shown in Fig. 1, Fig. 2.

| Technical parameters          | Value       |
|-----------------------------|-------------|
| Roll size/mm                | Ø850×1500   |
| Roll gap/mm                 | 5.9~6.0     |
| Casting speed/m·min⁻¹       | 1.0~2.0     |
| Melt pool height/mm         | 40~80       |

Table 2 Thermo physical properties of aluminum [11]

| Property                  | Value  |
|---------------------------|--------|
| $C_p$, J/(kg·°C)          | 1046   |
| $\rho$, kg/m³            | 2368   |
| $\Gamma$, W/(m·°C)       | 90.7   |
| $\Gamma'_s$, W/(m·°C)    | 218    |
| $T_m$, °C                 | 668.7  |
| $L_e$ kJ/kg               | 393.56 |

Fig. 1 Simulated results of twin-roll continuous casting aluminum thin strip solidification microstructure
By analysis, the average grain size and the average columnar crystals deviation of twin-roll continuous casting aluminum thin strip with different heat transfer coefficient and pouring temperature were measured, and the results are shown in Fig. 3, Fig. 4.

Fig. 2 Microstructure of the twin-roll continuous casting aluminum thin strip

![Microstructure Image]

Fig. 3 Influence of surface heat transfer coefficient on grain size in cross section

![Graph Image]
Influence of surface heat transfer coefficient on average grain size in cross section is shown in Fig.3. It can be seen from this figure that the mean grain size is insensitive to the changes of the cooling conditions—the heat transfer coefficient. Influence of pouring temperature on mean columnar crystals deviation in lengthwise section is shown in Fig.4. As can be seen from this figure, despite the increase of grain size, changes in the superheat of the casting have little effect on the grain orientation.
4. Conclusions

(1) A simple micro mathematical model for solidification structure simulation of twin-roll continuous casting thin strip is developed. In the model, the latent heat is treated with the enthalpy method, Moreover, the heterogeneous nucleation model, and columnar-to-equiaxed transition (CET) models are also introduced, together with the revising of dendrite growth dynamic model of KGT. Although the predicted results of the micro mathematical model are relatively consistent to the measured ones, some errors still exist due to many assumptions in the model.

(2) The average grain size of thin strip and the average columnar crystals deviation with different heat transfer coefficient and pouring temperature were measured. The predicted results of the micro mathematical model are relatively consistent to the measured ones. It is show that the established micro mathematical model is reliable, and it can predict parameters influence on solidification structure of twin-roll continuous casting thin strip.

Reference

[1] Bo Wang, Jie Yu Zhang, Xiang Mei Li, Wei Hua Qi. Simulation of solidification micro structure in twin-roll casting strip[J]. Computational Materials Science 49 (2010):S135–S139.

[2] Mingbo Yang, Fusheng Pan. Analysis about forming mechanism of equiaxed crystal zone for 1Cr18Ni9Ti stainless steel twin-roll thin strip[J]. journal of materials processing technology 209 (2009):2203–2211.

[3] Ch. Gras, M. Meredith, J. D. Hunt. Micro structure and texture evolution after twin roll casting and subsequent cold rolling of Al–Mg–Mn aluminum alloys[J]. Journal of Materials Processing Technology 169(2005):156–163.

[4] Yucel Birol. Analysis of macro segregation in twin-roll cast aluminum strips via solidification curves[J]. Journal of Alloys and Compounds 486 (2009):168–172.

[5] Sanjeev Das, N. S. Lim, J. B. Seol, H. W. Kim, C. G. Park. Effect of the rolling speed on micro structural and mechanical properties of aluminum–magnesium alloys prepared by twin roll casting[J]. Materials and Design 31(2010):1633–1638.

[6] Jian Zeng, Roger Koitzsch, Herbert Pfeifer, Bernd Friedrich. Numerical simulation of the twin-roll casting process of magnesium alloy strip[J]. journal of materials processing technology 209 (2009):2321–2328.

[7] H. T. Liu, Z. Y. Liu, Y. Q. Qiu, G. M. Cao, C. G. Li, G. D. Wang. Characterization of the solidification structure and texture development of ferritic stainless steel produced by twin-roll strip casting[J]. MATERIALS CHARACTERIZATION 60(2009):79–82.

[8] Rappaz, M., Gandin, Ch.-A.. Probabilistic modeling of micro structure formation in solidification process[J]. Acta Metall, 1993,41:345–352.

[9] Kurz, W., Giovanola, B., Trivedi, R.. Theory of micro structural development during rapid solidification[J]. Acta Metall, 1986,34:823–830.

[10] Flood, S. C., Hunt, J. D.. Columnar and equiaxed growth. I. A model of a columnar front with a temperature dependent velocity[J]. J. Cryst. Growth, 1987,82:543–552.

[11] Zhutang WANG, Rongzhang TIAN. Manual processing of aluminum and its Alloy[M]. Central South University Press, 1989,153-154.