Xu et al. Chin. J. Mech. Eng. (2018) 31:99
https://doi.org/10.1186/s10033-018-0299-1

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE Open Access

Effect of Oscillation Parameters to Flow Field in the Pool during the Oscillating Twin-Roll Strip Casting Process

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Abstract

During the oscillating twin-roll strip casting process, the quality of final products is directly influenced by the flow field distribution of molten metal in the pool. The variation in the flow field is caused by oscillating roller benefits, for homogeneous distribution of strip impurity, and decreasing the grain size. Thus, the quality of the strip could be improved. A numerical model was developed using the multiphase flow technology, coupled with heat transfer, fluid flow, solidification, and oscillation. Furthermore, a transient algorithm was adopted for simulating the oscillating twin-roll strip casting process of AlSi9Cu3 and 3104 aluminum alloy. This paper focuses on the flow distribution in the pool, in comparison with the traditional vertical twin-roll strip casting process, while the amplitude or frequency is changing with the definite value of casting velocity, roller diameter, nozzle angle, and the strip thickness. Consequently, the conclusions were experimentally validated by oscillating twin-roll 3104 aluminum alloy strip casting. Vibrating casting technology can change the flow field in the pool by vibration, which can improve the quality of the strip core.

Keywords: Flow field, Oscillating twin-roll strip casting, Solidification, Twin-roll strip casting

1 Introduction

Twin-roll casting (TRC) technology is one of the near net shape forming processes which can reduce production costs, energy, and wastage dramatically. In a traditional TRC process, the rotating axis of the rollers is fixed and the impurity deposit is in the center line with a steady flow field, which might lead to segregation, cracks and other defects [1–3]. Therefore, the oscillating twin-roll strip caster, created by Du et al. [4], with adopted mechanical oscillation, is able to adjust the oscillating amplitude of the roller through the different installation angles of a pair of eccentric suites.

The application of Computational Fluid Dynamics in TRC has been systematically introduced by Guthrie and Tavares [5, 6]. In addition, a more comprehensive mathematical model was established in order to study the influence of different nozzles to the temperature field and the distribution of solidified shell [7]. The distribution of the temperature field in the molten pool and the solidification end point in different roller gaps and diameters was studied by Zhang and Jiang [8, 9]. The impact of diverse casting velocity and temperature on the solidification point was analyzed by Li and Zhang [10]. Nonetheless, the solidification and the turbulence model was ignored by Li and Zhang. Recently, the free liquid surface wave model, considering the solidification and standard turbulence, was simplified by Sahoo et al. [11]. The effects of different casting velocities and super-heat on the solidification rate of the billet, during high speed casting and rolling of aluminum alloy was studied. The correctness of the mathematical model was verified by experiment on the solidification rate of the bullet shell.

In this paper, the distribution of the flow field in the molten pool of the casting and rolling pool of different amplitudes or the equivalent frequency with different amplitude is studied through numerical simulation. Furthermore, the effects of solidification and low Reynolds turbulence models on the numerical simulations were considered [12–14]. In addition, the influence of

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the pressure change on the solidification process must be considered because the distribution of the flow field is affected by the oscillation of the roller during the strip casting process and the change of the pressure in the molten pool.

2 Mathematical Model and Boundary Conditions

The mathematical model is based on the following assumptions:

(1) The molten metal is a Newtonian fluid, and the flow is considered in-compressible;
(2) Segregation is not taken into account during the solidification of molten metal in the molten pool, and the heat release process of phase transition between microstructure is neglected;
(3) There is no slip between the rollers and strip;
(4) There is no deformation of rollers and strips due to heat and same rotating velocity of rollers;
(5) A 3-D problem is simplified to a 2-D problem because the temperature and flow field effects are neglected due to the width of the nozzle which almost equals the width of the rollers;
(6) Thermal conductivity coefficient and viscosity of metal materials are functions of temperature;
(7) The physical parameters of casting roller are constant.

2.1 Governing Equation

All of the governing equations could be expressed by a general differential equation as follows [15]:

$$\frac{\partial}{\partial t}(\rho\phi)+\frac{\partial}{\partial x_{\mathrm{k}}}(\rho u_{\mathrm{k}}\phi)=\frac{\partial}{\partial x_{\mathrm{k}}}(T_{\phi}\frac{\partial\phi}{\partial x_{\mathrm{k}}})+S_{\phi}, \tag{1}$$

where ϕ is the transport variable, T_{ϕ} is the equivalent heat conduction and S_{ϕ} is the source term of the momentum or energy equation.

2.2 Low Reynolds Turbulence Model

Turbulence with a lower Reynolds number is the major molten pool flow during the oscillating twin-roll strip casting. Moreover, due to continuous change of the molten pool and roller boundary during the casting roller oscillation, the standard turbulence model of wall function in the numerical simulation could not be determined accurately. Instead, the properties of turbulence in the fluid, two phase zones, and the wall can be easily handled by a low Reynolds number turbulence model because it is not necessary to use a wall function. Thus, the low Reynolds number turbulence model proposed by Lam and Bremhorst was employed [16].

2.3 Solidification Model

The solidification was denoted using the Enthalpy-Porosity principle [17], and the liquid phase fraction β was introduced as follows:

$$\begin{cases}\beta=0, & T<T_S,\\ \beta=1, & T>T_L,\\ \beta=\frac{T-T_S}{T_L-T_S}, & T_S<T<T_L.\end{cases} \tag{2}$$

2.4 Application of the VOF Model

The VOF model relies on the fact that two or more fluids (or phases) are impermeable to each other. For each phase of the introduced model, a variable called the unit volume fraction is introduced. In each control volume, the sum of the volume fractions of all phases is 1. According to values of volume fractions, the variables and physical properties in any unit are representatives of either a phase or the multiphase mixture. Therefore, if the volume fraction of the phase q fluid in the unit is α_q, there are three possibilities:

(1) $\alpha_q=0$: There is no phase q fluid in the unit;
(2) $\alpha_q=1$: The unit is filled with the phase q fluid;
(3) $0<\alpha_q<1$: There is an interface between the phase q fluid and another phase or multiphase fluid.

2.5 Boundary Conditions

The difference between the oscillating and the traditional strip casting is that a roller in the process of casting is oscillating, which leads to repeated casting of the weld pool. The schematic of the oscillating twin-roll strip casting process is shown in Figure 1.

The boundary conditions at the entrance ("AB" in Figure 1) are:

$$\begin{cases}T=T_{\mathrm{in}}, u_x=0, u_y=u_{\mathrm{in}},\\ k=0.01u_{\mathrm{in}}^2, \varepsilon=\frac{k^{1.5}}{R_{\mathrm{noz}}}, P=P_0.\end{cases} \tag{3}$$

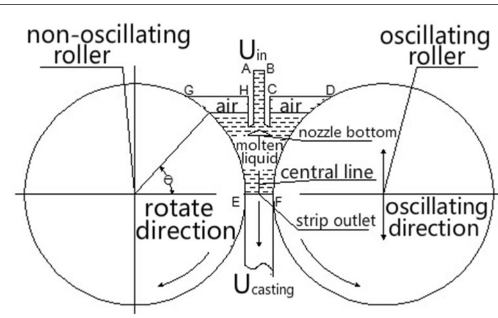


Figure 1 Schematic of the oscillating twin-roll strip casting process

The pressure outlet ("CD" and "GH" in Figure 1) is:

$$T = T_{\text{atmo}}, \quad P = P_0. \tag{4}$$

The tangential velocity of the solidification shell and the roll surface is consistent with the same velocity at the interface ("DF" in Figure 1) of the oscillating roller surface and the molten pool. This is due to no-slip conditions between the roller and strip. Therefore, the velocity boundary conditions of the roller surface contact elements are as follows:

$$\begin{cases} u_x = u_{\text{cast}} \cos\alpha, \\ u_y = u_{\text{cast}} \sin\alpha, \\ -\lambda_{\text{eff}} \frac{\partial T}{\partial n} = h_{\text{R}}(T - T_{\text{rol}}). \end{cases} \tag{5}$$

The interface surface of the non-oscillating roller and the molten pool ("GE" in Figure 1) is:

$$\begin{cases} u_x = u_{\text{cast}} \cos\varphi, \\ u_y = u_{\text{cast}} \sin\varphi, \\ -\lambda_{\text{eff}} \frac{\partial T}{\partial n} = h_{\text{L}}(T - T_{\text{rol}}). \end{cases} \tag{6}$$

The exit ("EF" in Figure 1) is:

$$u_x = 0, \quad u_y = u_{\text{cast}}. \tag{7}$$

The rest or the boundaries are adiabatic.

The oscillating displacement curve is:

$$S = A\sin(2\pi f \cdot t). \tag{8}$$

In Eqs. (3)–(8), $T_{\text{in}}$is the pouring temperature, u_{in} is the inlet velocity, u_x is the velocity of X direction, u_y is the velocity of Y direction, k is the turbulent kinetic energy, ε is the turbulent kinetic energy dissipation rate, R_{noz} is the hydraulic diameter of the nozzle, P_0 is the atmospheric pressure, T_{atmo} is the atmospheric temperature, u_{cast} is the casting velocity, α and φ are the units in contact with the right and left casting roller angle position respectively, λ_{eff} is the effective thermal conductivity of the metal solution, A is the amplitude, f is the frequency, t is time, h_{R} and h_{L} are the heat transfer coefficients on the right and the left side of the casting roller and the molten pool interface of convection respectively. For the convection exchange heat coefficient, the thermal contact resistance, the equivalent radiation convection exchange heat coefficient and the effects [18–22] of oscillating roller contact with the molten pool surface of the air gap thickness were considered. Therefore, the coefficients for the two sides of convection exchange heat were not exactly the same, but they both ranged between 4000 to 6000 $\text{W/m}^2\text{K}$ [23].

2.6 Determination of Numerical Solution

The oscillating strip casting process of one side casting roller is always rotating and oscillating, which causes the flow field change. Hence the transient algorithm was chosen for the simulation of the oscillating strip casting process [24] and the coupled algorithm for solving the pressure and velocity. The pressure interpolation was made by the Body Force Weighted, and the momentum, turbulent kinetic energy, turbulent kinetic energy dispersion rate and energy equations of the discrete schemed with second order upwind scheme. In the calculation process of the residual iterative convergence conditions are 1×10^{-4}, except 1×10^{-6} for the energy equation. Meanwhile, the initial internal flow field does not completely flow due to the transient algorithm. Therefore, the molten pool flow field velocity variation in one oscillating cycle is not stable and the law of the real production in the oscillating strip casting molten pool flow, can't be described. Consequently, it is necessary to monitor the velocity of some reference points that changes with time, in the molten pool, which stop the calculation until the reference velocity point size changes periodically with time.

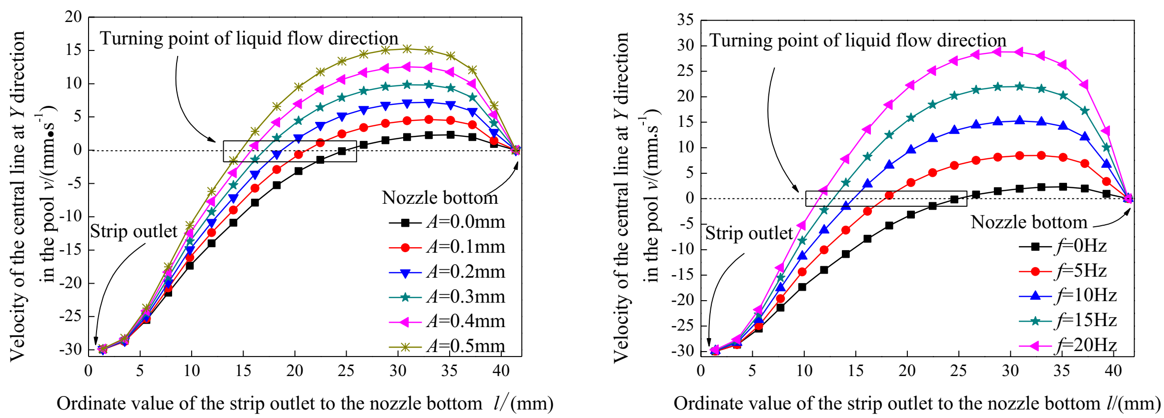
3 Numerical Simulation and Analysis of Results

There are four special positions in one sine oscillation cycle: the rising balance position, the peak, the down balance position and the trough. Based on the transient calculations and comparing the flow field velocity, four vital positions were also found in the flow field velocity of the center line. In addition, the velocity of the center line also periodically changes along with the oscillating roller. By comparing the simulated data, it was found that when the oscillating roller reached the rising or down balance position, the distribution of the flow field velocity of the center line also reached two extremes. This is quite different from the non-oscillating velocity of the center line. Instead, when the oscillating roller reached the peak or trough position, the velocity of the center line distribution was almost the same with that of the non-oscillating roller. Therefore, this research focuses on the comparisons between the velocity of the center line with and without oscillation. More precisely, different frequencies and amplitudes are investigated when the casting roller is in the two balance positions. (Directions X and Y are defined as the core connection direction of the two casting rollers and the casting direction respectively). The thermophysical parameters of the material and the basic parameters of the oscillating twin-roll strip caster for AlSi9Cu3 aluminum alloy is shown in Table 1.

The velocity distribution of the center line at the rising balance position is shown in Figure 2, (a) with constant

Table 1 Thermophysical properties and oscillating twin-roll strip casting parameters of AlSi9Cu3 aluminum alloy

Parameter	Value	Parameter	Value	Parameter	Value
Roller diameter *l* (mm)	160	Atmosphere temperature *T* (K)	300	Air specific *C* (J/kg)	1006.43
Velocity *v* (mm/s)	30	Liquids temperature *T* (K)	858.3	Atmosphere pressure *P* (Pa)	1.01235×10^5
Contact angle *a* (°)	40	Solidus temperature *T* (K)	777	Air viscosity *η* (Pa·s)	1.7894×10^{-5}
Strip thickness *h* (mm)	4	Latent heat *L* (J/kg)	4.17×10^5	Pouring temperature *T* (K)	878.3
Frequency *f* (Hz)	5, 10, 15, 20	Metal specific heat *C* ($J{\cdot}kg^{-1}K^{-1}$)	970	Amplitude *a* (mm)	0.1, 0.2, 0.3, 0.4, 0.5
Air density *ρ* (kg/m)	1.225	Metal density *ρ* (kg/m^3)	2.625×10^3	Contact resistance *f* (m^2K/W)	6×10^{-5}
Heat transfer coefficient *K* (W/m^2)	4000–6000	Air gap thermal conductivity *J* ($W{\cdot}m^{-1}K^{-1}$)	3.9×10^{-2}	Roller emissivity	0.5
				Aluminum alloy emissivity	0.4



a Same frequency (*f*=10 Hz) with different amplitude

b Same amplitude (*A*= 0.5 mm) with different frequency

Figure 2 Velocity of the central line in *Y* direction in the pool at the position of rising balance

frequency ($f = 10$ Hz) and different amplitude, (b) with constant amplitude ($A = 0.5$ mm) and different frequency. Negative velocity of the center line corresponds to the same direction with the strip casting, while positive velocity of the central line corresponds to the opposite direction. The velocity point of zero is the transition limit of the fluid velocity direction change. When there is no oscillation, the stream line is shown in Figure 3(a), the metal liquid below the inflection point is affected by the strip of the exit velocity, the flow has the same direction with the strip roll casting and the velocity increases. Above the inflection point, there are opposite and symmetric vortices, and the velocity of the center line is offset by the vortex. Therefore, the flow is opposite to the casting velocity. When the right roller oscillates, as shown in Figure 3(b), double vortices on both sides of the nozzle evaluate to a single vortex on the left side of the nozzle. The single left vortex is forced to gradually move closer to the left casting roller. The *Y* direction velocity of the center line is mainly controlled by the right oscillating roller. The inflection point of velocity direction changing move to the exit of the strip (Line 1) under the offset by the right oscillating roller with the strip casting velocity. The greater the amplitude/frequency, the greater the instantaneous velocity of the casting roller up, which offset with the exit velocity, leading to the *Y* direction velocity distribution below the inflection point. Above the inflection point, the metal liquid flow is relatively simple, the greater the amplitude/frequency, the greater the influence of the oscillation on the metal liquid flow. Moreover, the velocity increases and then decreases under the influence of no slip at the bottom of the nozzle.

Figure 4 shows the velocity of the center line in the *Y* direction at the down balance position. When the oscillating roller is at the down balance position, as shown in Figure 3(c), the casting roller movement direction is the same with the direction of the casting. The velocity of the center line in the *Y* direction is determined by the casting and the oscillating roller velocity. Thus, when the frequency/amplitude is constant, the greater the

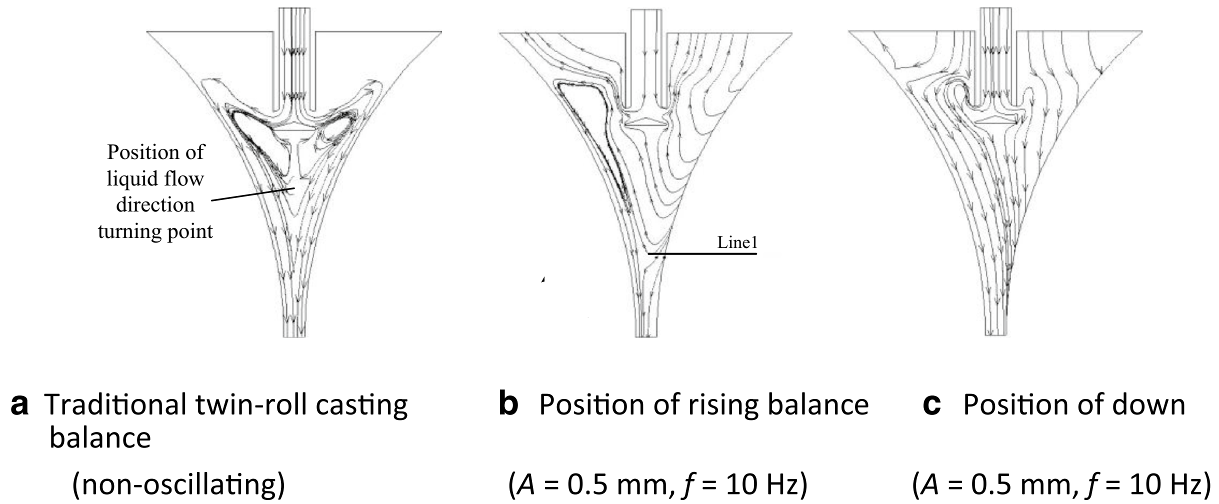


Figure 3 Stream line in the pool for different roller positions

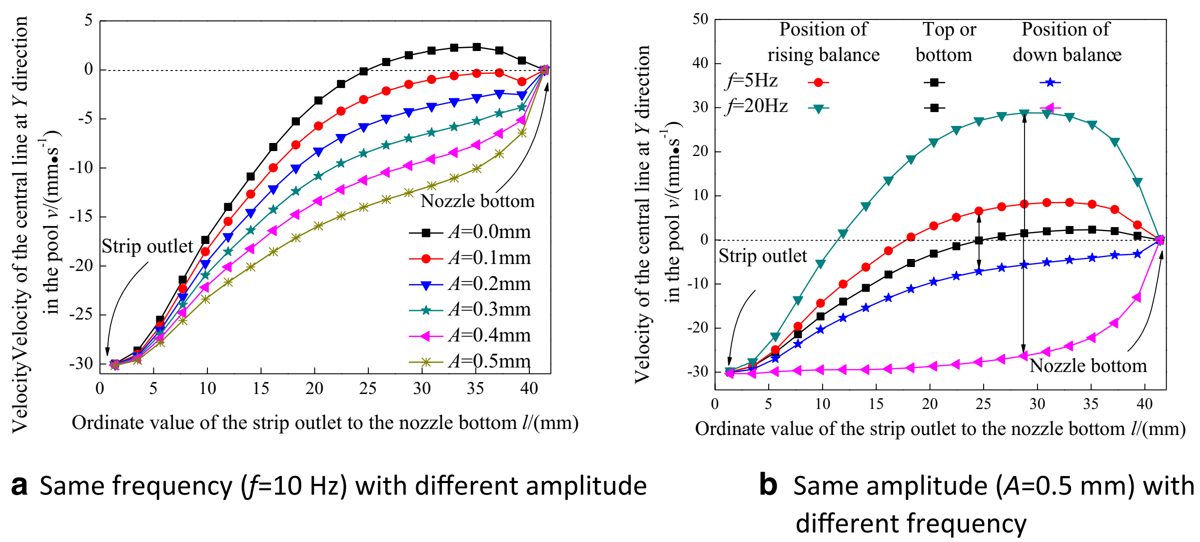


Figure 4 Velocity of the central line in the *Y* direction in the pool at the position of down balance

amplitude/frequency, the greater the velocity of casting roller movement, the greater the influence on center line flow field, and the greater the velocity of the center line.

Figure 5 shows the velocity of the central line in *Y* direction in the pool in one oscillation cycle under same frequency, with different amplitude, the same amplitude, and with different frequency. Changes in the velocity of the center line in one cycle are increased with the increase of amplitude or frequency.

During traditional twin-roll strip casting, the metal flow on both sides of the nozzle in the molten pool is symmetrical and the velocity of the center line in *X* direction is almost zero. While twin-roll strip casting is oscillating periodically, the velocity of the center line in *X* direction is affected, and the change along the *X* direction is similar with that along the *Y* direction. The center line velocity in one cycle increases with the increasing of amplitude or frequency. However, because the metal flow in the molten pool is still dominated by the *Y* direction (casting roller direction), there is little change in the velocity of the center line in the *X* direction.

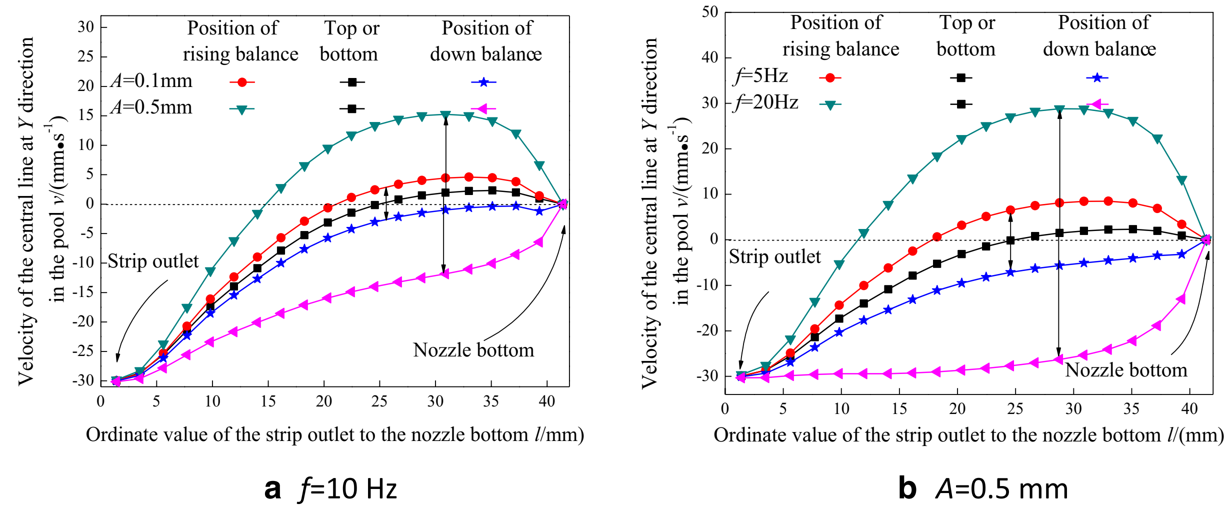


Figure 5 Velocity of the central line in the *Y* direction in the pool in one oscillation cycle

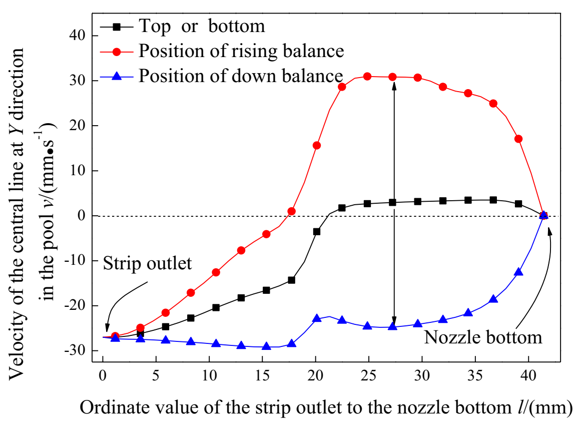


Figure 6 Velocity of the central line in the *Y* direction in one oscillation cycle

4 Experimental Verification

The same method was used to simulate the oscillating casting process of aluminum alloy 3104. The velocity of the center line in the *Y* direction in one oscillating cycle with amplitude $A=1$ mm and frequency $f=10$ Hz is shown in Figure 6. The distribution and the change of velocity are basically the same with the oscillating casting process of the aluminum alloy AlSi9Cu3. The experiments for the aluminum alloy 3104 were carried out using the oscillating twin-roll strip caster. The first group is the traditional twin-roll strip casting, the second group is the oscillating twin-roll strip casting and the specific experimental parameters are shown in Table 2.

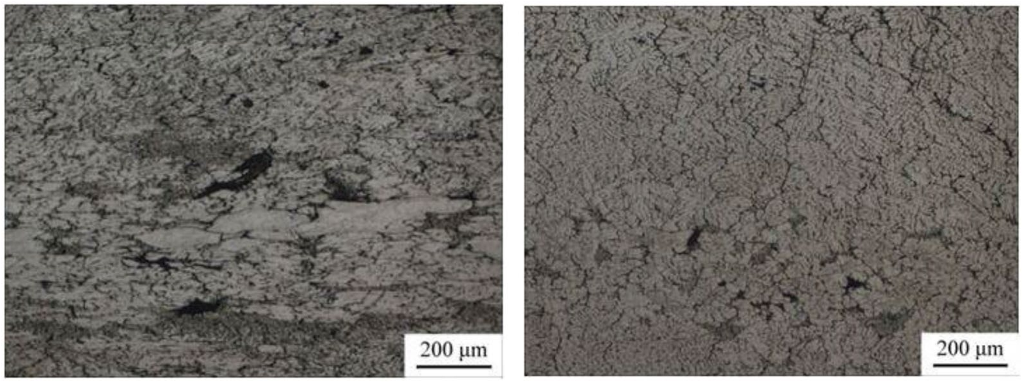
The micro-structure of the longitudinal-section of the 3104 aluminum alloy strips near the central line for (a) conventional twin-roll casting and (b) oscillating twin-roll casting ($A=1$ mm, $f=10$ Hz) are shown in Figure 7. The grain is relatively long and narrow in Figure 7(a) while relatively more uniform size grains appear in the right side of Figure 7(b). Therefore, the variation of flow field caused by an oscillating roller, results in homogeneous distribution of strip impurity and decreased grain size.

5 Conclusions

(1) Simulations showed that the flow field in the molten pool is not in steady state but periodically changes, during the oscillating twin-roll strip casting process.
(2) With the amplitude/frequency increasing along the direction of casting velocity, the inflection point of

Table 2 Experimental table of traditional twin-roll strip casting and oscillating twin-roll strip casting

Parameters	Pouring temperature *T* (K)	Casting velocity *v* (mm/s)	Strip thickness *h* (mm)	Frequency *f* (Hz)	Amplitude *a* (mm)
Traditional twin-roll strip casting	973	27	4	0	0
Oscillating twin-roll strip casting	973	27	4	10	1



a Conventional twin-roll casting **b** Oscillating twin-roll casting (A=1 mm, f=10 Hz)

Figure 7 Longitudinal-section micro-structure of 3104 aluminum alloys strips

the molten pool center linear velocity decreases, the range of the changing direction of velocity increases and the scope of stirring expands. At the same time the scope of inclusions expands by affected, more uniform of the inclusions distribution, components and uniformity in the macro strip is achieved.

(3) With the amplitude/frequency increasing, the velocity changes dramatically in one oscillating cycle. While the stirring intensity increases, the collision between grains is strengthened, therefore, the micro-structure is refined and the quality of the strip is improved.

Authors' Contributions

Z-QX, D-QZ wrote the manuscript; Z-RM was in charge of the whole trial; S-HX, F-SD assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

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Competing Interests

The authors declare that they have no competing interests.

Funding

Supported by National Natural Science Foundation of China (Grant No. 51374184), and Hebei Provincial National Natural Science Foundation of China (Grant No. E2013203342).

Publisher's Note

Received: 14 September 2016 Accepted: 13 November 2018
Published online: 05 December 2018

References

1. C Gras, M Meredith, J D Hunt. Microdefects formation during the twin-roll casting of Al-Mg-Mn aluminum alloys. *Journal of Materials Processing Technology*, 2005, 167: 62-72.
2. Z Lv, F S Du, Z J An, et al. Centerline segregation mechanism of twin-roll cast A3003 strip. *Journal of Alloys & Compound*, 2015, 643: 270-274.
3. L L Chang, J H Cho, S K Kang. Microstructure and mechanical properties of twin roll cast AM31 magnesium alloy sheet processed by differential speed rolling. *Materials and Design*, 2012, 34: 746-752.
4. Feng-Shan Du, Zhi-Qiang Xu, Peng-Cheng Lu, et al. Oscillating twin roll strip caster: China, 200710185377. 9. 2008.
5. R I L Guthie, R P Tavares. Mathematical and physical modelling of steel flow and solidification in twin-roll/horizontal belt thin-strip casting machines. *Applied Mathematical Modelling*, 1998, 22: 851-872.
6. R P Tavares, R I L Guthie. Computational fluid dynamics applied to twin-roll casting. *Canadian Metallurgical Quarterly*, 1998, 37(3-4): 241-250.
7. N Zhang, P Tang, M M Zhu. Research metal delivery system of twin-roll thin strip continuous caster for magnesium alloys. *Materials Review*, 2010, 24(16): 237-240.
8. X M Zhang, Z Y Jiang, X H Liu, et al. Simulation of fluid flow, heat transfer and micro-segregation in twin-roll strip casting of stainless steel. *Journal of Materials Science and Technology*, 2006, 22(3): 295-300.
9. X M Zhang, Z Y Jiang, L M Yang, et.al. Modelling of coupling flow and temperature fields in molten poll during twin-roll strip casting process. *Journal of Materials Processing Technology*, 2007, 187-188: 339-343.

10. Q Li, Y K Zhang, L G Liu, et al. Effect of casting parameters on the freezing point position of the 304 stainless steel during twin-roll strip casting process by numerical simulation. *Journal of Materials Science*, 2012, 47: 3953-3960.
11. S Sahoo, A Kumar, B K Dhindaw, et al. Modeling and experimental validation of rapid cooling and solidification during high-speed twin-roll strip casting of Al-33 wt pct Cu. *Metallurgical and Materials Transactions B*, 2012, 43(4): 915-924.
12. Z H Zhang, H L Wu, L Feng, et al. Application of numerical simulation technologies for continuous casting mold. *Journal of Iron and Steel Research*, 2016, 28(5): 1-6.
13. San-Zhong Wang. Numerical simulation and experimental research on flow field during the twin-roll strip casting process. *Yanshan University*, 2015. (in Chinese)
14. Da-Ming Nie. Simulation and analysis of the flow-field of molten pool during strip casting. *Northeastern University*, 2013. (in Chinese)
15. Cheng-Jian Wang. Numerical simulation research on twin-roll steel strip casting. *Northeastern University*, 2009: 17–20. (in Chinese)
16. M A Taha, N A Ei-Mahallawy, M T Ei-Mestekawi, et al. Estimation of air gap and heat transfer coefficient at different faces of Al and Al-Si castings solidifying in permanent mould. *Materials Science and Technology*, 2001, 17: 1093-1101.
17. D Pal, J Bhattacharya, P Dutta, et al. An enthalpy model for simulation of dendritic growth. *Numerical Heat Transfer, Part B: Fundamentals*, 2006, 50(1): 59-78.
18. C S Li, B G Thomas. Thermomechanical finite-element model of shell behavior in continuous casting of steel. *Metallurgical and Materials Transactions B*, 2004, 35(B): 1151-1172.
19. C G Kang, Y D Kim. A thermal elastic-plastic finite-element analysis to roll-life prediction on the twin roll strip continuous casting process. *Metallurgical and Materials Transactions B*, 1997, 28(B): 1213-1225.
20. Wei Zhang. Study on instantaneous interfacial heat transfer during near rapid solidification process. *Shanghai Jiao Tong University*, 2011. (in Chinese)
21. M Tian, Z Q Xu, Z Lv. Mathematic model of interfacial transfer for twin-roll strip casting based on boundary temperature of molten pool. *Foundry Technology*, 2016(2): 268-272.
22. Yao Li. Simulation and experiment study in the vibration of twin-roll strip casting process. *Yanshan University*, 2011. (in Chinese)
23. W Zhang, G F Liang, C Q Wang. A simulator to determine transient interfacial hear transfer in strip casting. *Baosteel Technology*, 2009(4): 32-34. (in Chinese)
24. W Zhang. Study on instantaneous interfacial heat transfer during near rapid solidification processes. *Shanghai Jiao Tong University*, 2011. (in Chinese)