

Mechanism and simulation of external cooling in aluminum casting-rolling process^①

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Abstract: External cooling technology is one of the key technologies to realize fast-casting-rolling process of aluminum, i. e. using compulsive cooling on the external surface of rollers and aluminum plate to improve the cooling ability of system, increase casting-rolling speed, and enhance the quality of aluminum plate. Heat transfer model of casting-rolling process was proposed and the characteristics of the temperature field of roller-plate system were analyzed. The influences of external cooling surface of the plate and the roller on the temperature field of the roller and the aluminum plate and the casting-rolling speed were discussed, and the relationship between external cooling and internal cooling were also analyzed. Experiment results show that, with the increase of casting-rolling speed, the influence of cooling plate surface on increasing casting-rolling speed was gradually decreased, but that of cooling roller surface was enhanced. Different mechanisms of external cooling plate surface and roller surface for improving casting-rolling speed account for this phenomenon.

Key words: aluminum; casting-rolling; external cooling

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1 INTRODUCTION

Casting-rolling molding technology is a new molding technology, which is clear and rapid^[1, 2]. It is applied to complete the molding by making use of the excellent fluidness and lower deformation resistance of materials, during the transformation process of material from liquid state to semisolid state and finally to solid state. The aluminum casting-rolling technology has become the main technology for process of aluminum strip due to its advantages of low cost and reduced energy consumption. Fast casting-rolling technology for super thin materials is the most advanced technology which could push this field to another peak of high level, high efficiency, high quality and short cycle^[3, 4]. The key of that is to improve cooling ability of casting-rolling system, and the external cooling technology is the most important. So, the research on mechanism of external cooling in casting-rolling process has a great contribution to the development of external cooling technology and the design of external cooling scheme.

2 BASIC EQUATIONS AND MATHEMATIC MODEL OF HEAT TRANSFER IN ALUMINUM CASTING-ROLLING PROCESS

The principle of the casting-rolling molding

technology is shown in Fig. 1. The molten aluminum is poured through casting jaws into the wedge-molding area between two casting-rolling rollers, and then is molded as various sizes of strips. The heat released during solidification and cooling process of aluminum transfers to rollers through the contact, and the circulate-cooling water flowing through the inside of rollers continuously cooled rollers, which is a guarantee for the casting-rolling process. Casting-rolling rollers are different from general rolling rollers. They play two roles as water-cooling crystallizers and rolling rollers^[1]. The heat exchange process of casting-rolling molding is shown in Fig. 2.

In casting-rolling process, heat transfers mainly on the vertical plane to the axes of rollers, and the temperature fields of roller and aluminum strip are steady under continuously working condition. Therefore, two-dimensional steady heat transfer equation is adapted to simulate and analyze it^[5, 6], and analyzing upper-half of casting-rolling system is enough because the system is symmetrical about center plane of aluminum strip. The boundary conditions of simulation analysis are as follows:

- 1) The entrance of casting-rolling area is an isothermal boundary;
- 2) The symmetrical center plane of aluminum strip is under heat insulation boundary condition;

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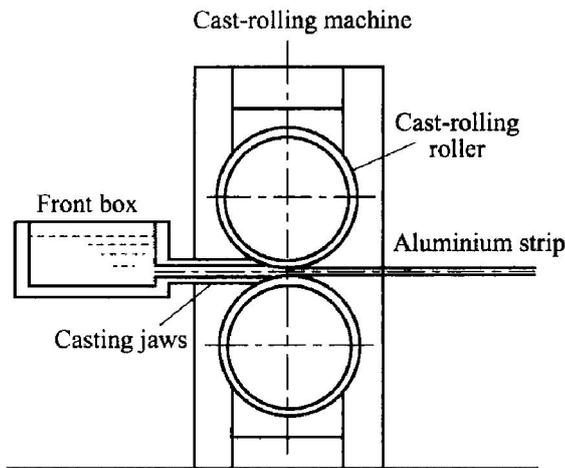


Fig. 1 Model of casting-rolling of aluminum material

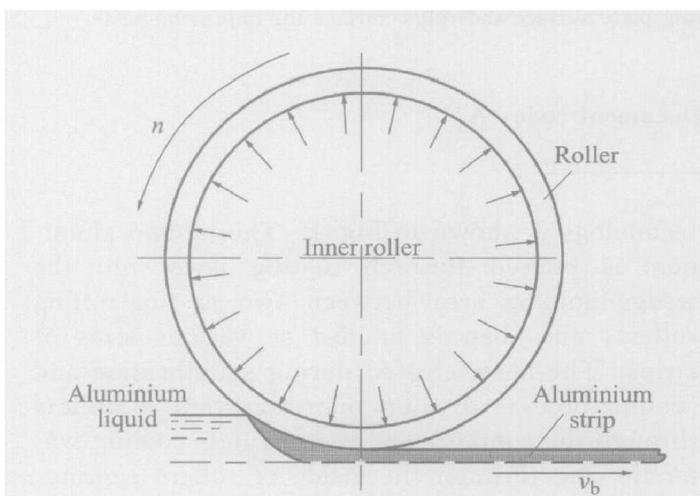


Fig. 2 Heat exchange process on interface of casting-rolling

3) The contact interfaces between water, gas and rollers-plate are under the third kind boundary condition.

According to the characteristics of casting-rolling system, the simulation analysis adopts fixed coordinate system. Cylindrical coordinate system is adopted for the roller and the origin is fixed at the center of roller. In this system, it is defined that r axis is the diameter direction of roller, φ is the rotation direction of roller. Cartesian coordinate system is adopted for aluminum plate and the origin is fixed on the center plane of entrance of casting-rolling area. In this system, X axis is the conveying direction, Y axis is along the height direction of the plate.

For the roller, the heat transfer partial differential equation under conditions of no internal heat and no phase changes is given by

$$\alpha \left[\frac{\partial^3 T_g}{\partial r^2} + \frac{1}{r} \frac{\partial T_g}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T_g}{\partial \varphi^2} \right] + \omega \cdot \frac{\partial T_g}{\partial \varphi} = 0 \quad (1)$$

For aluminum plate, the phase changes take place in the process of solidification, large amount

of solidification heat is released. Here the solidification heat is regarded as inner heat^[7], and the heat transfer partial differential equation can be expressed as

$$\alpha \left[\frac{\partial^3 T_b}{\partial x^2} + \frac{\partial T_b}{\partial y^2} \right] + \left[u \frac{\partial T_b}{\partial x} + v \frac{\partial T_b}{\partial y} \right] + \alpha \frac{\partial q_{in}}{\lambda} = 0 \quad (2)$$

where T_g is the temperature of roller, T_b is the temperature of aluminum plate, t is time, ω is the rotational speed, u and v are the velocities of micro-cell along X and Y direction respectively, α is the thermal diffusivity of roller material, $\alpha = \lambda / \rho c$, λ is the thermal conductivity, ρ is the density of material, c is the specific heat capacity, $\frac{\partial T}{\partial t}$ expresses the local change rate of temperature with time (it equals zero under the steady condition), and $\omega \frac{\partial T_g}{\partial \varphi}$ and $u \frac{\partial T_b}{\partial x} + v \frac{\partial T_b}{\partial y}$ express the temperature change induced by mass flow of roller and plate.

The heat transfer partial differential equation reflects the heat transfer characteristics in casting-rolling process. It is the combination of the two kinds of heat transfer modes, including heat movement of micro-particle and the heat transfer of macro movement of roller (along φ direction) and aluminum plate (along X or Y direction)^[8, 9].

3 CHARACTERISTICS OF TEMPERATURE FIELD OF ROLLER-PLATE SYSTEM IN CASTING-ROLLING PROCESS

Fig. 3 and Fig. 4 show the curves of changes of steady temperature field of roller and aluminum plate under the conditions of casting-rolling thickness $H_b = 8$ mm of aluminum plate at 1 m/min speed with 37Cr3NiMoV as roller material, the roller diameter $D_g = 1000$ mm and the thickness $H_g = 50$ mm. S_g and S_b represent the distances between temperature points and outer surface of roller and aluminum plate respectively. Fig. 3 shows the temperature of the surface of roller reaches the maximum 421 °C at the position of 28 mm in casting-rolling area, whose total length is 70 mm; the temperature is 347 °C at the exit position of casting-rolling area, and the temperature of the surface of roller decreases gradually backward this area. The temperature reaches the minimum 45 °C at the position of 8 mm in the front of casting-rolling area; and increases gradually due to the influences of high temperature of working area. On the inner surface of roller contacted with cooling water, the maximum temperature is 31.5 °C, the average is 27 °C, which indicates that the temperature difference is only 7 °C between the average temperature of roller inner surface and cooling water.

It can be seen from Fig. 4 that because of the

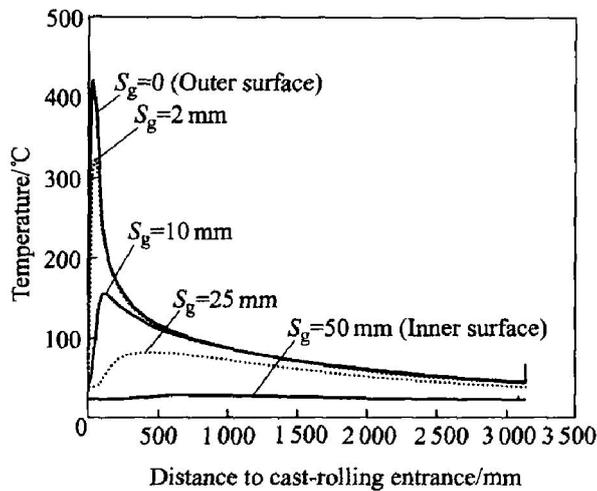


Fig. 3 Variation of roller temperature field

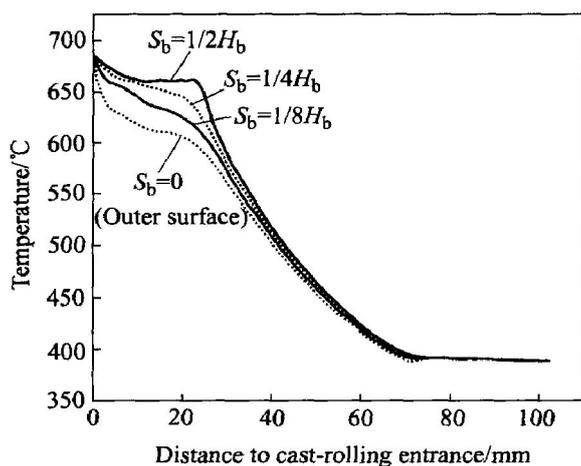


Fig. 4 Variation of plate temperature field

emission of solidification heat, the temperature in every layer of aluminum plate changes nonlinearly in casting-rolling area, and a temperature platform exists. The phenomenon is much more obvious in the center layer of plate. The lengths of layers in liquid cave zone, semisolid state zone and solid state zone can be obtained from positions when the temperatures of layers are at liquidus ($t_L = 660\text{ }^\circ\text{C}$) and solidus ($t_L = 640\text{ }^\circ\text{C}$). These length values reflects the solidifying and crystallizing process of aluminum plate in casting-rolling area.

4 INFLUENCES OF EXTERNAL COOLING ON TEMPERATURE FIELD OF ROLLER-PLATE SYSTEM

Under the condition of fast casting-rolling, the heat exchange quantity increases a lot. Large amount of heat can not be taken out by circulate-cooling water in time, and accumulates on external surface of roller, which results in the external temperature of roller increasing obviously. Finally, on the casting-rolling interface, the temperature difference between the roller and the plate decrea-

ses, and the cooling ability of system decreases also. In order to solve this problem and realize fast casting-rolling for super thin materials, it is very important to develop an external cooling technology during fast casting-rolling process. The external cooling on the surfaces of roller and plate can take out the heat, remove the heat accumulation and improve the cooling ability.

The starting position of external cooling zone should be put near the exit position for improving effects. The scheme of external cooling is shown in Fig. 5. The compressed air and cooling medium are atomized and sprayed at nozzle, and then cool the exit surface of roller and plate. The external cooling zone is 1 000 mm long from exit position of casting-rolling zone along roller or plate surface, the heat exchange coefficient of external cooling is $5\,000\text{ W}/(\text{m}^2 \cdot \text{ }^\circ\text{C})^{[10]}$.

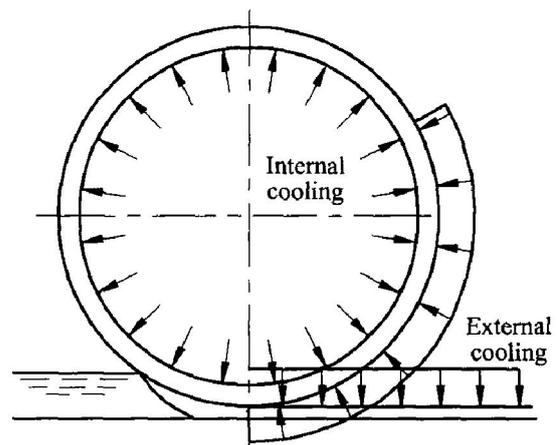


Fig. 5 Model of external cooling

4.1 Influences of external cooling of plate surface on temperature field of roller-plate system

Fig. 6 shows the influences of external cooling of plate surface on the temperature field of roller and aluminum plate under the conventional condition of casting-rolling 8 mm aluminum plate.

Comparing Fig. 6(a) with Fig. 3, it can be seen that: 1) the maximum temperature ($421\text{ }^\circ\text{C}$) on roller surface is decreased by $0.13\text{ }^\circ\text{C}$ and still at the same position; 2) the temperature of exit ($336\text{ }^\circ\text{C}$) in casting-rolling zone is decreased by $11\text{ }^\circ\text{C}$; 3) the minimum temperature on roller surface reaches $44.5\text{ }^\circ\text{C}$ at 8 mm forward casting-rolling zone, and is decreased by $0.5\text{ }^\circ\text{C}$. It is indicated that the influence of external cooling of plate surface on roller surface is much more obvious at the exit position of casting-rolling zone than that in other positions.

Comparing Fig. 6(b) with Fig. 4, it can be concluded that there are two obvious effects of external cooling on the plate surface:

1) At the exit position of casting-rolling area, the temperature of the aluminum plate decreases

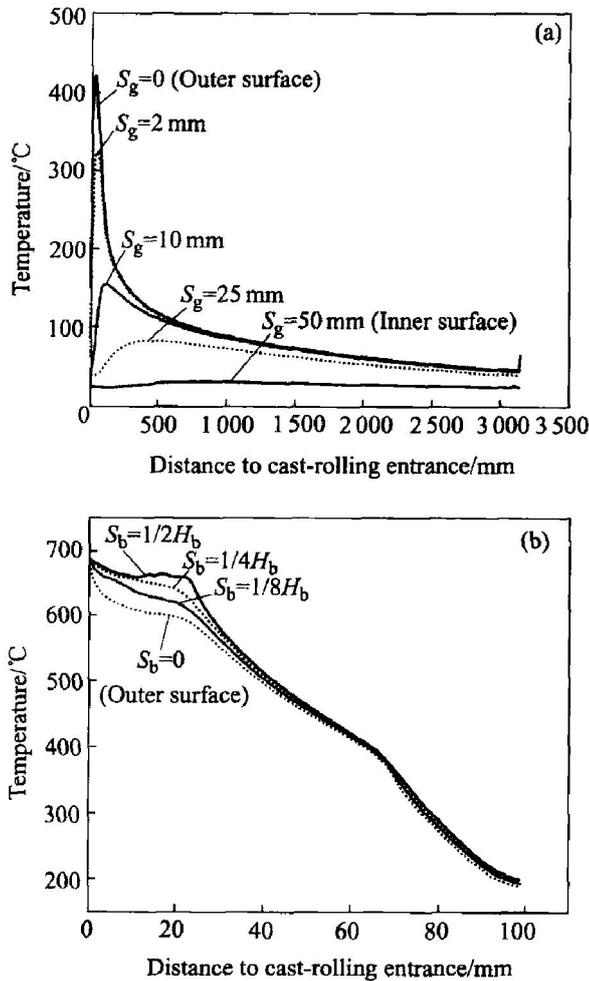


Fig. 6 Influence of external cooling of plate surface on temperature field of roller-plate system under conventional casting-rolling condition
(a) —Rollers; (b) —Aluminum plate

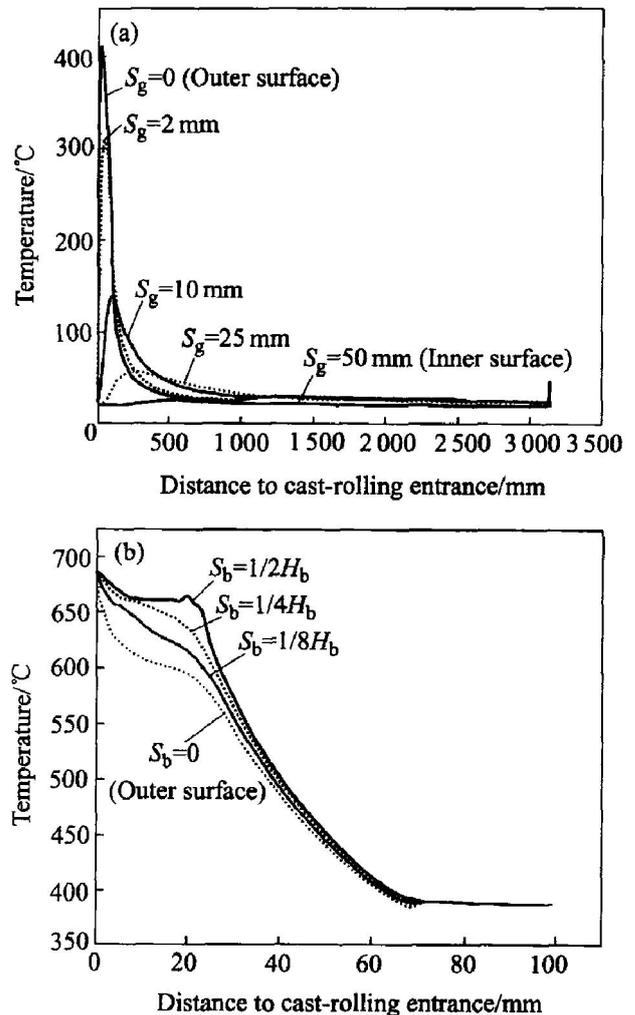


Fig. 7 Influence of external cooling of roller surface on temperature field of roller-plate system under conventional casting-rolling condition
(a) —Rollers; (b) —Aluminum plate

remarkably, from 400 °C to 375 °C;

2) The temperature of aluminum plate out of casting-rolling area decreases fast, and the average temperature decreases to 200 °C at 30 mm from the exit of area.

4.2 Influences of external cooling of roller surface on temperature field of roller-plate system

Fig. 7 shows the influences of external cooling of roller surface on the temperature field of roller-plate system under the conventional condition of casting-rolling 8 mm aluminum plate.

Comparing Fig. 7(a) with Fig. 3, it can be seen that, the maximum temperature on the roller surface is 410.5 °C, decreased by 10.5 °C and still at the same position; the temperature at the exit of area is 335 °C, decreased by 65 °C.

In the external cooling zone, it is obvious that the temperature of external surface is lower than that of internal surface. At the end of external cooling zone, the temperature of roller surface decreases to the minimum value, 24.5 °C, which is

decreased by 20.5 °C. Subsequently, the temperature of roller surface increases a little to 28 °C; and decreases to 20.05 °C at the 8 mm forward the casting-rolling area. Then it goes up gradually because of the influences of high temperature area in casting-rolling.

Comparing Fig. 7(b) with Fig. 4, it can be seen that the temperature of aluminum plate decreases by some degrees in the tail part of casting-rolling area, from 400 °C to 385 °C at the exit position, and consequently, the temperature at other positions changes.

4.3 Influences of external cooling on typical temperature points under various casting-rolling conditions

The influences of external cooling on the maximum and minimum temperatures of roller surface, as well as temperatures of aluminum plate at exit position under various casting-rolling conditions are shown in Table 1.

Table 1 Influences of external cooling on typical temperature points under various casting-rolling conditions

Thickness of plate/ mm	Without external cooling			External cooling on surface of plate			External cooling on surface of rollers			
	Cast-rolling speed/ ($\text{m} \cdot \text{min}^{-1}$)	t_{max} on surface of rollers/ $^{\circ}\text{C}$	t_{min} on surface of rollers/ $^{\circ}\text{C}$	t on surface of plate at entrance/ $^{\circ}\text{C}$	t_{max} on surface of rollers/ $^{\circ}\text{C}$	t_{min} on surface of rollers/ $^{\circ}\text{C}$	t on surface of plate at entrance/ $^{\circ}\text{C}$	t_{max} on surface of rollers/ $^{\circ}\text{C}$	t_{min} on surface of rollers/ $^{\circ}\text{C}$	t on surface of plate at entrance/ $^{\circ}\text{C}$
8	1	424.8	45.5	400	422.3	45.0	297.0	410.0	23.1	393.0
7	1.242	415.2	52.0	400	413.0	53.0	322.0	384.3	23.7	385.0
6	1.572	406.0	60.0	400	404.0	60.0	346.0	362.0	24.5	379.0
5	2.07	417.0	69.8	400	392.0	67.0	361.0	352.2	25.7	365.0
4	2.85	382	82.0	400	378.0	82.0	382.0	339.8	27.1	354.0
3	4.2	366.0	94.5	400	363.0	94.0	389.6	314.0	36.0	345.8
2	7.2	340.9	114.7	400	340.6	114.6	396.2	281.0	40.7	335.1

It is shown from Table 1 that under conventional casting-rolling condition, the casting-rolling speed increases with the decrease of thickness of plate, and the temperature of roller surface decreases with the increase of casting-rolling speed. So, the cooling ability of system increases with the increase of casting-rolling speed, for example, the speed of casting-rolling of 8 mm plate is 1 m/min, but that of 2 mm plate is 7.2 m/min instead of 4 m/min. With the increase of casting-rolling speed, under the condition of keeping the exit temperature of plate steady, the maximum temperature of roller surface decreases gradually and the minimum temperature increases at the same time.

Both the maximum and minimum temperatures of roller surface decrease under the condition of external cooling on the plate surface, but only in a small range. The external cooling of plate influences the temperature field less and less with the casting-rolling speed going up.

The external cooling of plate surface influences the exit temperature of plate obviously, but it decreases with the increase of casting-rolling speed. The further research shows that, if the starting position of external cooling does not reach the exit position of casting-rolling, for example, 20 mm distance, the influences of external cooling on plate disappear.

The maximum and minimum temperatures of roller surface, and the exit temperature of plate decrease under the condition of external cooling on roller surface. Furthermore, the influences of external cooling on roller surface increase continuously with the increase of casting-rolling speed. The further research shows that if the starting position of external cooling does not reach the exit position of casting-rolling area, the influences on the temperature field of roller-plate system will keep steady or change in a narrow range.

5 INFLUENCES OF EXTERNAL COOLING ON IMPROVING CASTING-ROLLING SPEED

All above shows that external cooling on surfaces of roller and plate can decrease the temperature certainly. It is useful to improve casting-rolling speed. Hereon, keeping the exit temperature of plate at 400 $^{\circ}\text{C}$, the influences of external cooling of roller and plate surfaces on casting-rolling speed are recorded. The results are shown in Table 2. Table 2 shows that under all conditions, external cooling on surface of plate can improve the speed, and the improvement is greater at low velocity conditions. For example, at 1 m/min, the velocity under the condition of external cooling on surface of plate is 17% more than that under normal condition; and when 7.32 m/min, it is just 1.38%.

External cooling on surface of roller can also increase the casting-rolling speed, which is adverse to the influences of external cooling on surface of plate. The influence is great under the conditions of high speed. For example, at 1 m/min, the velocity under the condition of external cooling on surface of roller is 11% more than that under normal condition; and when 7.32 m/min, it attains 32%.

Under the condition of external cooling on surface of plate, the heat of casting-rolling area is brought out with aluminum plate and the rolling velocity is heightened. There is a competition between the velocity of plate and the transfer velocity of external cooling, which are adverse to each other, i. e. when the former increases, the latter will turn lower and in the casting-rolling area the influences of cooling part will turn down. What's more, in the further experiments, it is indicated that if the initial position of external cooling part is

not in the export position of casting-rolling area, e. g. a 20 mm distance between them, then little change will happen on the speed of casting-rolling.

Under the condition of external cooling on surface of roller, more heat in casting-rolling area is brought out by the rise of difference of temperature in the working area, which is caused by the lower temperature of rollers in the entrance part, and then, the casting-rolling speed is increased. The higher the plate velocity is, the more heat the roller brings out. With the rise of temperature of out-working area and entrance part of roller, the effects of cooling is enhanced. Therefore, increasing the velocity of plate is good for enhancing the effects of cooling roller on improving casting-rolling speed. Obviously, technology of external cooling on surface of roller will probably become the main tendency in the field of external cooling technology.

6 INTERACTION BETWEEN EXTERNAL COOLING AND INTERNAL COOLING

When external cooling is added to the system, the method of heat transfer is changed, the speed

of casting-rolling goes up, and a new heat balance is formed, i. e., cooling power of system equals exothermic power of aluminum plate, which is the sum of cooling power of internal cooling and external cooling.

In order to investigate the coupling action between internal cooling and external cooling, we made a series of experiments. It was supposed that the coefficient of heat transfer of interfaces was invariable ($K_w = 10\,000\text{ W}/(\text{cm}^2 \cdot \text{K})$), which means that the cooling conditions are steady. The thickness of aluminum plate was 2 mm so that it reached the condition of fast cast-rolling. When the conditions of casting-rolling figuration which the temperature outside was 400 °C were satisfied, changes of some related capabilities under different external cooling conditions were recorded in Table 3. From Table 3, it can be seen that when intensity of external cooling rises, the cooling power of external cooling, the casting-rolling speed and the exothermic power of plate all increase, and the cooling power of system matches for the exothermic power of plate. But the cooling power of internal cooling goes down gradually, from 458 kW (the initial power) to 128 kW, and the proportion

Table 2 Influences of external cooling on improving casting-rolling speed

Thickness of plate/mm	Cast-rolling speed without external cooling/(m • min ⁻¹)	External cooling on surface of plate		External cooling on surface of rollers	
		Cast-rolling speed/(m • min ⁻¹)	Relative ratio/%	Cast-rolling speed/(m • min ⁻¹)	Relative ratio/%
8	1	1.17	17	1.1	10
7	1.242	1.39	12	1.392	12.1
6	1.572	1.71	8.8	1.8	14.5
5	2.07	2.195	6	2.4	16
4	2.85	2.97	4.2	3.38	18.6
3	4.2	4.32	2.86	5.32	26.7
2	7.2	7.3	1.38	9.5	32

Table 3 Interaction between external cooling and internal cooling

Parameter	Changing rule of parameters					
Heat exchange coefficient of external cooling/(W • cm ⁻² • K ⁻¹)	0	1 000	2 000	4 000	7 000	10 ⁴
Cooling power of external cooling/kW	0	158	255	361	434	470
Cooling power of internal cooling/kW	458	348	279	205	154	128
Cooling power of air/kW	12	9	7.6	5.9	4.7	2.8
Cooling power of system/kW	470	515	542	572	593	601
Cast-rolling speed/(m • min ⁻¹)	7.2	8.10	8.52	9.00	9.33	9.48
Releasing power of heat on aluminum material/kW	470	515	542	572	593	601
Lowest temperature on surface of roller/ °C	112	87.4	72	50.8	36.8	30.7
Highest temperature on surface of roller/ °C	343	326	315	304	296	292

in system decreases from 97.4% (the initial proportion) to 21.3%. It can be concluded that external cooling is more effective for bringing out the heat, because most of the heat released from the plate and accumulated on the surface of roller in the process of cast rolling has no time to transfer into the working area, and external cooling changes the way of heat transfer which turns down the effects of internal cooling.

On the other hand, the cooling capacity of the system can be enhanced by the bigger intensity of external cooling. It is because that both the minimum and the maximum temperature of roller decrease, and the temperature difference in the casting-rolling interface increases at the same time.

7 CONCLUSIONS

1) A numerical model of the heat transfer process in casting-rolling for aluminum material was built up. Simulation and analysis of temperature field in roller-plate system were done, and some basic principles of transfer of heat were concluded.

2) Simulations of plate under external cooling condition show that the external cooling plate can promote the casting-rolling speed; but the velocity competition counteracts the effects, and they turn down following the increase of casting-rolling speed. When the thickness of plate is 8 mm, the speed is increased by 17%, and when the value is 2 mm, 1.38% higher only.

3) Simulations of roller under external cooling condition show that the velocity of roller is promoted by decreasing the temperature of entrance part. Effects of external cooling are better in higher speed because the temperature of roller increases with speed. When the thickness of plate is 8 mm, the speed is increased by 10%; and when 2 mm, 32% higher. So, in an external cooling plan for super thin and fast casting-rolling, the external cooling of surface of roller should be put in the first place. External cooling medium with higher efficiency and more suitable external cooling zone are necessary for the promotion of casting-rolling speed and decrease of entrance temperature of working area.

4) According to the research of interaction between external cooling and internal cooling, the

cooling capacity and casting-rolling speed are promoted when the intensity of external cooling is enhanced. But during this process, paths of heat transfer are also changed, so the cooling power of internal cooling decreases. The cooling power of system is not equal to the sum of cooling power of internal cooling and external cooling, but turns to another coupling action of internal and external cooling under a new balance condition.

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