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Formation Mechanism and Influence Factors of the Sticker between Solidified Shell and Mold in Continuous Casting of Steel

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Abstract: Based on the stress characteristics of primary solidified shell in the mold, formation model of the shell's sticker is established according to the theory of mechanical strength, and the mechanism and internal factors of the shell tearing are analyzed by the model. Furthermore, based on the measured data of many stickers in a slab-continuous caster, the influence of casting process factors on the sticker is analyzed statistically. The possible causes for the stickers in the studied caster are discussed. The results provide a reference for optimizing the continuous casting production process and effectively preventing the occurrence of the sticker from the source.

Keywords: continuous casting, sticker breakout, mold, solidified shell, casting process factors

Introduction

The sticker breakout is a severe accident in continuous casting which frequently happens. It not only severely affects the smooth production of continuous casting, but also damages the continuous casting equipment and reduces the metal yield. The sticker breakout has become one of the key factors restricting the development of the high-speed continuous casting and wide-thick-plate continuous casting technology. Solving sticker breakout is significant for the smooth production of continuous casting and production of high-quality slab. Now two methods [1] are used to solve the sticking continuous casting. First, improve the casting process factors inducing the sticker and proactively prevent against the sticker from the source. Second, develop effective mold breakout alarming system. For a complicated mold metallurgy process, not only the cracking sensitive steel will be frequently cast, but the casting steels are diversified, so casting is difficult. Especially it is difficult to continuously ensure the coordination and match of casting process factors under high-speed continuous casting. Improved casting process factors cannot fully avoid the shell's sticker. But if the formation mechanism of sticker can be scientifically recognized, the influence law of the casting process factors on sticker can be grasped, and the casting process factors can be correctly improved and occurrence rate of shell sticking will be effectively reduced. Therefore, an in-depth study on the formation mechanism and influence factors of the solidified shell's sticker inside the mold is carried out, which can provide scientific basis for optimization of the onsite casting process.

Since the 1990s, the formation mechanism and influence factors of sticker breakout [2–7] have been studied enough at home and abroad, and the following conclusion is provided. The direct inherent factor leading to the sticker breakout is bad lubrication between primary solidified shell and mold near the meniscus, which makes the friction on the primary shell exceed its yield strength, resulting in the tearing. Different factors leading to bad shell's lubrication are the external factors, e. g. casting powder, mold oscillation, mold level fluctuation, casting speed, degree of superheat heat, etc. Thus, the conclusion can be made that the sticker's formation is related to bearing state of the primary shell. This paper first analyzes the tearing mechanism of the sticking shell from the stress state of the primary solidified shell, constructs the tearing model of the sticking shell according to mechanical strength theory, then validates the model by many examples of stickers based on the practical measurement data in casting, quantitatively analyzes the influence law of the casting process factors on sticker's formation, discovers the specific sticker's occurrence reasons, and improves the casting process factors inducing sticker purposefully.

Formation mechanism of the sticker

The sticker inside the mold mainly starts from the primary solidified shell near the meniscus. Analyzing the stress

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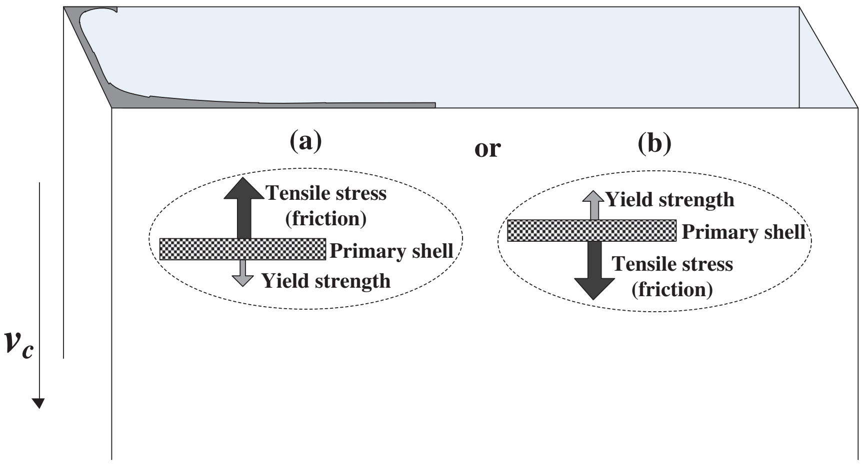

Figure 1: Stress state of primary solidified shell under up/down oscillation of the mold.

state on the primary solidified shell is very important for studying the tearing formation and influence factors of the sticker. The stress state of the primary solidified shell inside the mold is shown in Figure 1. The primary solidified shell near the meniscus mainly suffers from the friction and the static pressure of liquid steel is small. The gravity of the primary shell and the buoyancy of liquid steel can be ignored. The up/down oscillation of the mold and down movement of the slab will generate friction on the surface of the shell. The friction is divided into liquid friction and solid friction in accordance with the friction state between the shell and mold. The casting powder will mainly exist as the liquid near the meniscus and takes on the major function of liquid lubrication. The action of static pressure of liquid steel near the meniscus can be ignored, so the friction acting on the primary shell is the liquid friction and can be calculated according to the formula eq. (1) [8, 9].

$$F_l = \frac{\eta(v_m - v_c)}{\delta} \tag{1}$$

where F_l is liquid friction in unit area, N/m^2; η is the viscosity of casting powder, Pa· s; v_m is the upward oscillation velocity of the mold, m/s; v_c is the casting speed, m/min; and δ is the thickness of liquid slag layer, mm.

The tensile stress on the shell is caused by the friction inside the mold and can be calculated by formula eq. (2) [8].

$$\sigma_p = \frac{\int_0^L F_l dx}{D} = \frac{\eta(v_m - v_c)L}{\delta D} \tag{2}$$

where L is the distance from the meniscus, cm and D is the shell thickness at location L, mm.

In order to ensure that the primary shell is not torn, the maximal tensile stress on the shell should not exceed the yield strength σ_s according to the first strength theory [10], as shown in formula eq. (3). The maximal tensile stress on the shell can be obtained from the formulas eqs (2), (4) and (5). The result is shown as the formula eq. (6).

$$\sigma_s > [\sigma_p]_{\max} \tag{3}$$

$$v_m = \frac{2\pi fh}{1000}\cos\left(\frac{2\pi ft}{60}\right) \tag{4}$$

$$D = K\sqrt{\frac{L}{v_c}} \tag{5}$$

$$[\sigma_p]_{\max} = \frac{\eta(2\pi fh + v_c)}{\delta K}\sqrt{Lv_c} \tag{6}$$

where h is the mold oscillation amplitude, mm; f is the mold oscillation frequency, min^{-1}; and K is the solidification constant, $mm/min^{1/2}$. If the mold sinusoidal oscillation is used and the oscillation velocity is as shown in formula eq. (4), the maximal oscillation velocity is $0.002\pi fh$, m/min. The shell thickness D is calculated according to the solidification square root law, as shown in formula eq. (5).

To substitute the obtained maximal tensile stress into the eq. (3), inequality eq. (7) can be obtained, as follows.

$$\sigma_s \delta K > \eta(0.002\pi fh + v_c)\sqrt{Lv_c} \tag{7}$$

The bigger the left value or the smaller the right value of the inequality eq. (7) is, the less possible the shell will be torn. This inequality can reflect the conditions of the primary shell's sticker well. And this inequality shows that the main factors affecting the primary shell tearing and sticking include yield strength σ_s, liquid slag layer thickness δ, casting powder viscosity η, casting speed v_c, mold oscillation amplitude h, and oscillation frequency f. The yield strength σ_s reflects the influences of the steel performance and liquid steel temperature. The shell with a higher temperature and lower strength is more sensitive to be torn. The steel's strength will reduce with temperature growth and the closer it gets to steel liquid level, the higher the temperature will be, making the shell most easily torn near the liquid level. Or when the degree of superheat is too high, which results in the high temperature of the shell near the meniscus, the strength of the primary shell will accordingly reduce and the tearing sensitivity of the shell will grow. The liquid slags the layer thickness δ and the casting powder viscosity η reflect the performance of casting powder and liquid-level fluctuation. If the liquid slag layer is thicker and the viscosity of casting powder is small, the shell will not be easily torn and stuck and the casting powder can lubricate well. If the liquid level fluctuates too much, the liquid casting powder cannot be supplied and the liquid slag layer becomes thinner. The product of the oscillation amplitude h and oscillation frequency f reflects the influences of mold oscillation. If the amplitude is fixed and the oscillation frequency is higher, the primary shell will be easily torn. Similarly, if the vibration frequency is fixed and the amplitude is higher, the primary shell will also be easily torn. If the casting speed v_c is higher, the shell tearing sensitivity and occurrence probability of the sticker will increase. Rapid change of casting speed can also interfere the timely supply of mold powder and then the liquid slag layer will become thinner. It will inevitably affect the lubrication between the shell and copper plate and the shell tearing sensitivity will grow.

Analysis on casting process factors affecting sticker

Based on the above theoretical analysis, the casting process factors affecting the actual sticker are further investigated through the following field experiment. This experiment is carried out in a straight-curved slab-continuous caster. The caster has two strands, an arc radius of 9.5 m, and the casting slab section size is $230 \times (900 \sim 2{,}150)\ mm^2$. The operation casting speed is 0.80 ~ 2.03 m/min. The corresponding mold in the caster is a combined straight mold with the length of 900 mm, which is comprised of four copper plates: broad face fixed side, broad face loose side, narrow face left, and narrow face right. The width of the mold can be adjusted according to the slab width. In order to detect the formation and propagation behavior of the sticker, more rows of thermocouples in high density are embedded in mold copper plates for monitoring local temperature variation at different locations: 6 rows of 12 columns, a total of 72 thermocouples are embedded in each broad face; 6 rows of 2 columns, a total of 12 thermocouples are embedded in each narrow face. In total, 168 thermocouples are installed in the four copper plates.

Measured data from the slab-continuous caster are collected and sorted for nearly 10 months. According to the actual breakout record, sticker's alarm record, thermocouples' temperature, casting speed and mold level change, etc., 31 samples of slab sticker are obtained. By these samples, the influence of casting process factors (such as casting speed, mold level fluctuation, degree of superheat heat, slab dimension, etc.) on the stickers is analyzed statistically.

Casting speed

Table 1 shows the stickers' times and frequency under different casting speeds for the slabs with the width of 1,500 ~ 1,550 mm. The frequency of stickers is equal to the stickers' times over the corresponding casting heats. The stickers under casting speeds of 0.8 and 0.9 m/min occur at the initial stage of casting process, which are not to be considered. Under casting speeds of 1.0 ~ 1.2 m/min, the frequency of stickers will grow significantly at a high casting speed. Because if the casting speed is higher, the solidified shell becomes thinner inside the mold, and meanwhile the consumption of casting powders will reduce, and the powders will be easily distributed more unevenly inside the mold. So, under high-speed condition, flow-in conditions of the powders are easier to deteriorate and even liquid slags are broken, giving rise to direct contact between the primary shell and copper plate and thereby generate the sticker. Proper casting powder is also one important means to avoid the sticker at high casting speed. For the slabs with the width of 1,500 ~ 1,550 mm, improper physical and chemical performance of casting powder is one key reason for high incidence of stickers.

Table 1: Number of stickers under different casting speeds.

Slab dimension, mm²			230 × (1,500 ~ 1,550)		
Casting speed, m/min	0.8	0.9	1.0	1.1	1.2
Stickers' times	1	1	3	2	15
Frequency of stickers, times/heat	–	–	0.00256	0.00272	0.00505

Mold level fluctuation

Normally, the liquid level of the mold fluctuates within 3 mm. Mold level fluctuation prior to sticking is investigated by the above 31 samples of the sticker, as shown in Table 2. From the table, mold level fluctuation prior to sticking is bigger or equal to 4 mm in 22 stickers. The bigger liquid-level fluctuation is one key factor of inducing sticker. As shown in Figure 2, the liquid-level fluctuation reaches about 9 mm prior to one sticker breakout. When the liquid-level fluctuation is bigger, it will affect the liquid slag which uniformly flows into the gap between the copper plate and shell, and uniformity of primary solidification of the shell.

Degree of superheat heat

As shown in Figure 3, the degree of the superheat of four samples is over the required normal range in effective 27 samples of the sticker, especially when the degree of the superheat is too low, e. g. for the sample 22, the degree of the superheat is only 1 °C, the melting rate of the casting powders is reduced, and insufficient flow-in liquid slag leads to this sticker. If the degree of the superheat is too high, it will reduce the strength of the shell near the meniscus and increase the sticking risk too. Proper degree of superheat will facilitate melting and lubrication of the casting powders and improve the uniform distribution of casting powders. So the degree of superheat is one key factor of affecting sticker and the

Table 2: Relationship between level fluctuation prior to sticking and number of stickers.

Mold level fluctuation prior to sticking, mm	≤ 3	4	5	6	≥ 7	total
Number of stickers	9	10	7	3	2	31

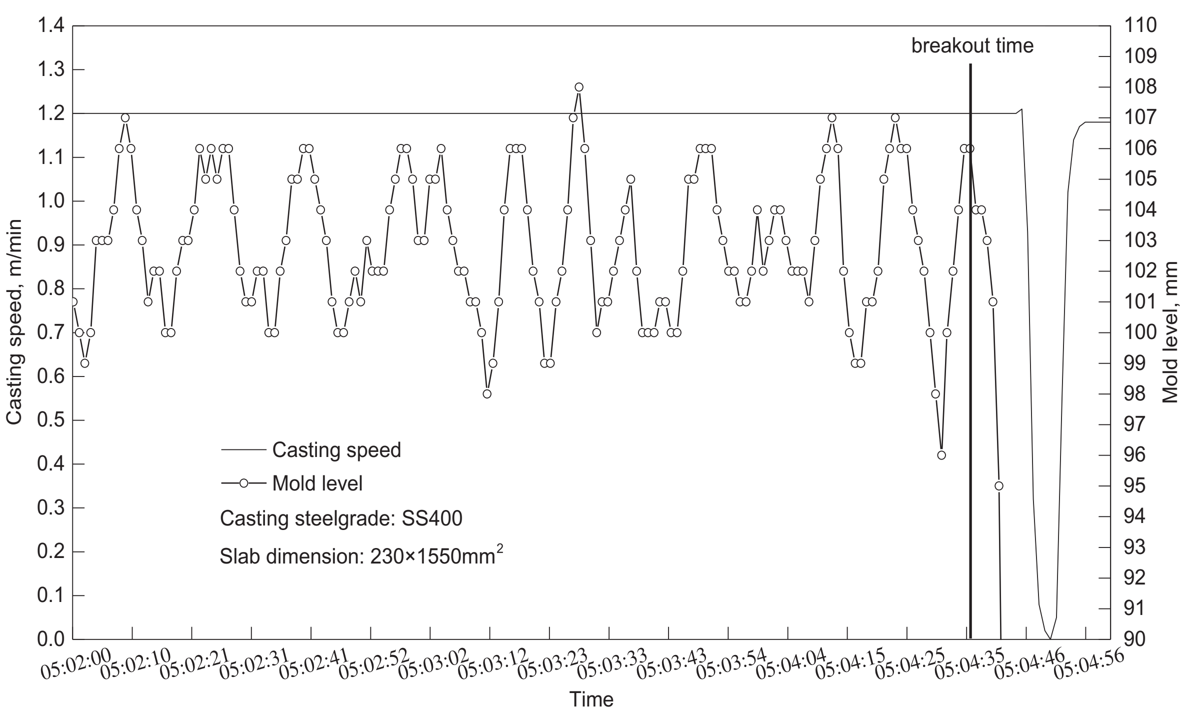

Figure 2: A sample of sticker caused by bigger liquid-level fluctuation.

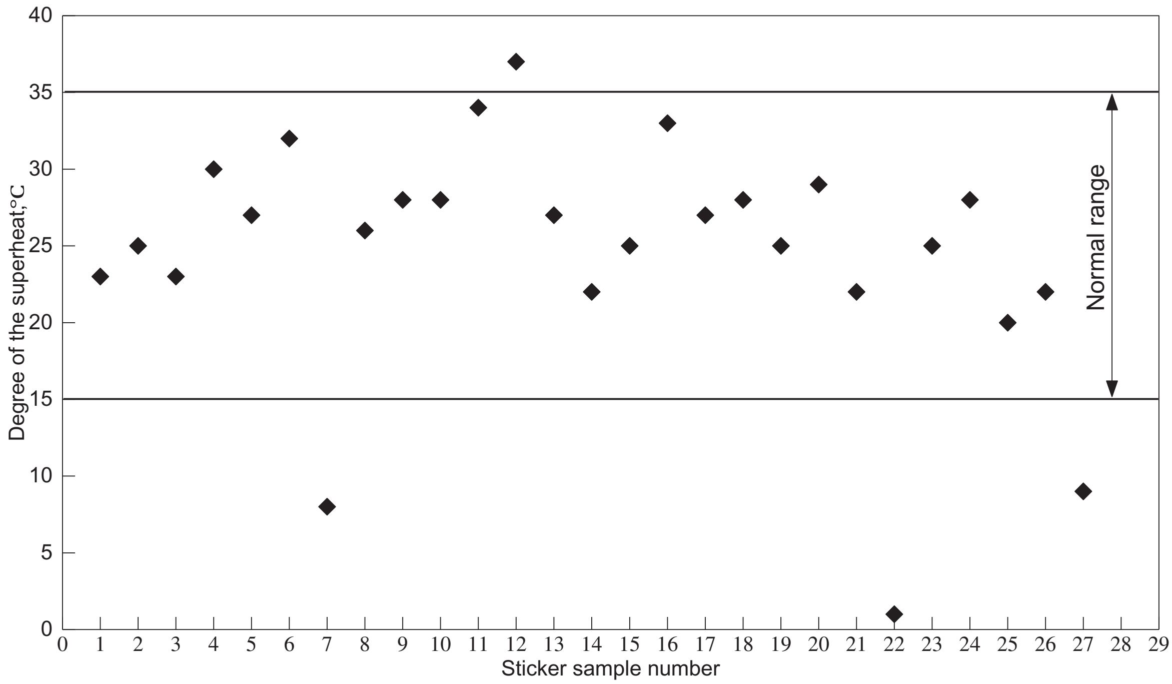

Figure 3: Effect of degree of the superheat on slab sticker.

casting temperature should be stably controlled to be within the proper range.

Slab dimension and sticker's position

Table 3 shows that the sticker's position of slabs with medium and small width may be located at the middle and corner. The sticker's positions of the wide slab mainly occur at the middle of the broad face and are related to many field conditions, such as insertion depth and side holes' design of the submerged entry nozzle. For the slab, the possibility of sticker at the middle of the broad face is high, which is given by the two narrow faces featuring high cooling and shrinkage. The shell will protrude outward at the middle of the broad face under the action of static pressure of molten steel. The shell is thinner, the liquid slag layer becomes thinner, and the shell is easy to directly contact the copper plate and stick.

Table 3: Relationship between slab dimension and sticker's position.

Slab width, mm	Number of corner stickers	Number of medium stickers
1,300	1	1
1,500	4	16
1,550	0	2
1,800	0	6
2,000	0	1

Mold cooling

To ensure uniform solidification of the shell in slab-continuous casting, generally heat flux ratio of narrow and broad face for the mold is controlled to be within 0.8 ~ 0.9. Table 4 shows that the heat flux ratio of narrow and wide face is over 0.9 and the heat flux ratio is lower on the broad face in the 6 counted sticker breakout samples. It indicates that the broad face cooling is weaker and the narrow face cooling is stronger under the existing process condition, so the cooling water volume of the broad face should be properly increased. The heat flux of the narrow face can be properly weakened via the narrow side taper, cooling water volume and casting powders to ensure uniform cooling and solidification of the slab. Figure 4 shows that the heat flux of the narrow face is significantly higher than that of the wide face prior to breakout and fluctuates much. It may be caused by nonuniform flow-in of the casting powders due to higher mold level fluctuation. It will make the shell directly contact the cooper plate, increase the friction, and generate the sticker. From Figure 5, the heat flux of the narrow face is significantly higher than that of the wide face, which indicates that the

Table 4: Average heat flux in 3 min before a sticker breakout.

Sticker breakout sample	Casting speed, m/min	Heat flux of each face of mold, MW/m^2				Heat flux ratio of narrow and broad face
		Fixed side	Loose side	Left side	Right side	
1	0.9	0.8910	0.9087	1.0136	1.0861	1.09 ~ 1.28
2	1.0	0.9038	0.9454	1.2924	1.2507	1.26 ~ 1.53
3	1.1	1.1403	1.1686	1.2008	1.0873	0.90 ~ 1.08
4	1.1	1.0387	1.0447	1.2984	1.0855	0.99 ~ 1.49
5	1.2	1.0599	1.0470	1.0854	1.0356	0.98 ~ 1.31
6	1.2	1.0199	1.0591	1.4085	1.3994	1.29 ~ 1.41

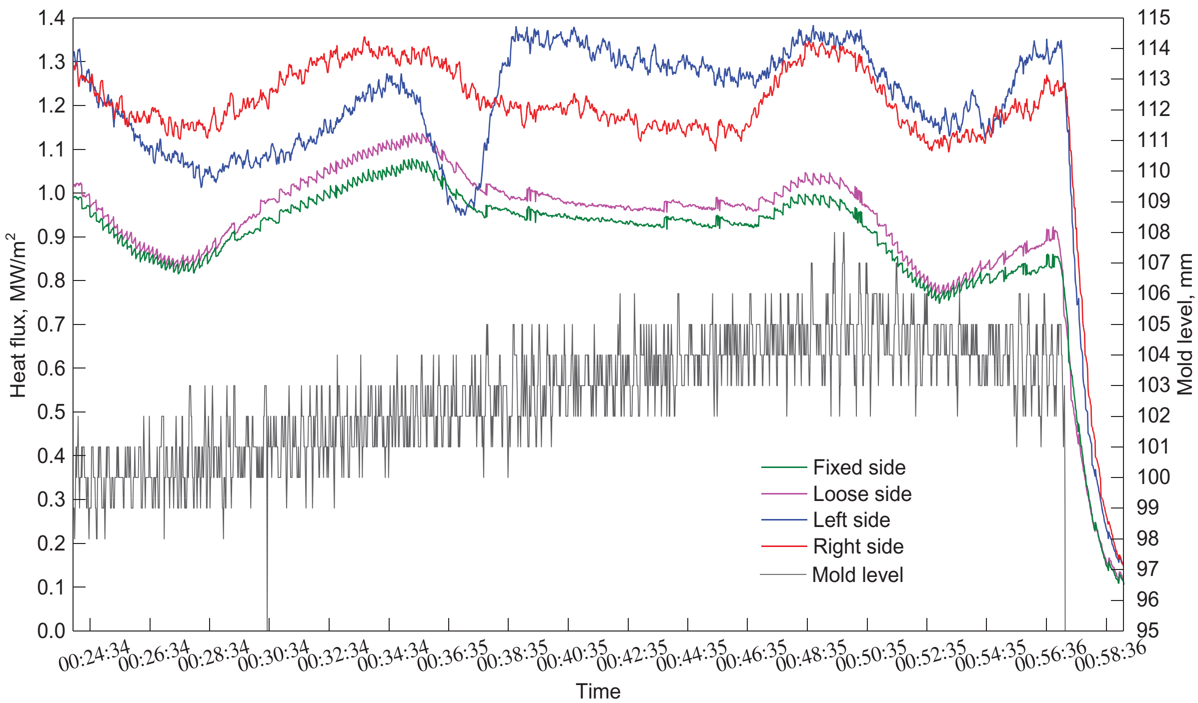

Figure 4: Heat flux variation of each face of the mold before breakout for sample 2.

narrow face is excessively cooled. It is found that before this sticker breakout, the heat flux of each face of the mold does not change obviously. So it can be seen that after sticking, the propagation behavior of the sticker cannot be effectively identified by the heat flux variation.

Conclusions

This paper establishes the tearing model of the shell's sticker according to the mechanical strength theory based on the stress characteristics of primary solidified shell inside the mold, analyzes the inherent formation mechanism of the shell's sticker, gets the inherent factors affecting the shell tearing and sticking, including yield strength, liquid slag layer thickness inside the mold, viscosity of casting powder, casting speed, mold oscillation amplitude and frequency, and qualitatively studies the law of their influences on sticker.

The influence of casting process factors on the sticker is investigated according to the actual measurement data of plentiful samples of actual stickers. On the one hand, the investigation results have verified theoretical formation model of the shell's sticker. Analysis results of actual data are consistent with the qualitative analysis of theoretical model. On the other hand, it is found that the current possible reasons inducing stickers include

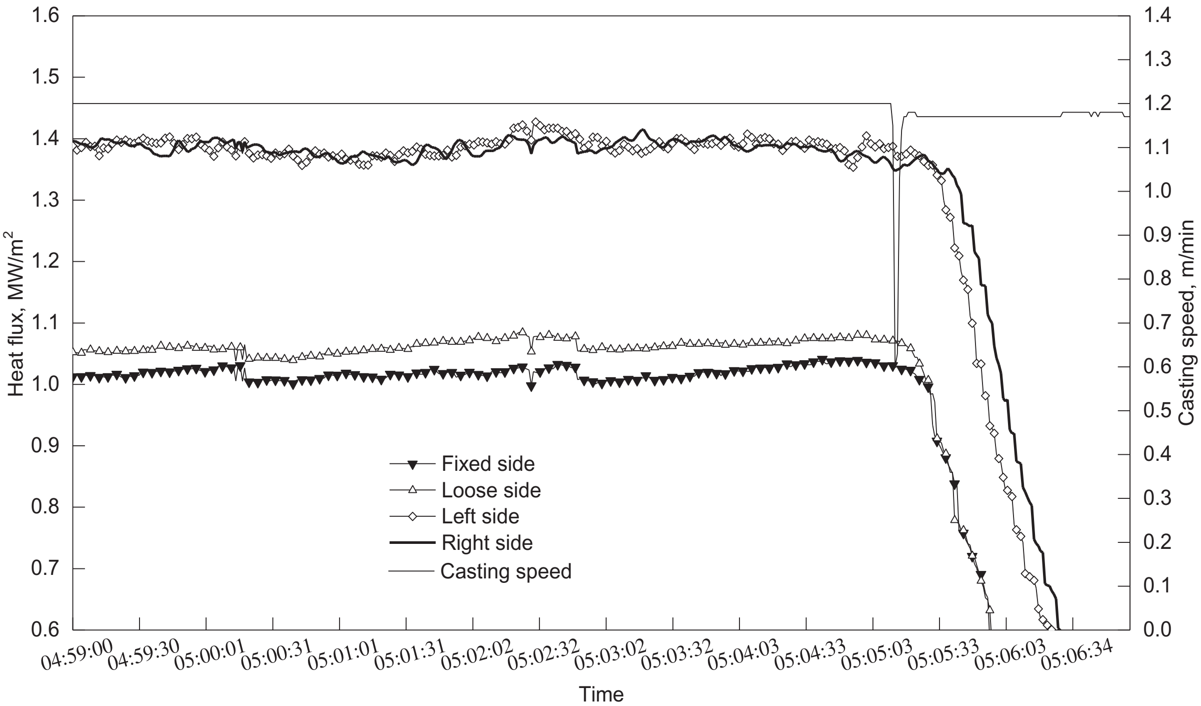

Figure 5: Heat flux variation of each face of the mold before breakout for sample 6.

understability of casting powder operation condition, too low degree of superheat of molten steel, too big fluctuation of liquid level, weaker cooling of broad face of the mold, excessive cooling of narrow face, etc.

Proper casting process parameters are the foundation and guarantee for realizing stable and efficient continuous casting. To proactively prevent against sticker from the source, it is necessary to reasonably design the casting process parameters, such as casting powder, submerged entry nozzle and mold taper, and make sure to get proper and stable casting degree of superheat, develop a rational mold cooling system for uniformity of the cooling and solidification of slab, and reasonably control the heat flux of the mold.

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