The Shell Surface Force Caused by Mould Friction during Slab Continuous Casting

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(Received on August 29, 2007; accepted on November 27, 2007)

In continuous casting, the lubrication and friction between the mould and the initial solidified strand shell play an important role for achieving the high speed casting and producing a good surface quality of the product. Investigation of the frictional behavior is therefore essential for getting a better online control of the mould processes. In the present work, the measurement of shell surface force caused by mould friction was performed during the slab continuous casting. Friction force was calculated to investigate the periodical variations as well as the effect of tensions and pressures on the solidified shell. Also the comparison of the mould friction in sinusoidal and non-sinusoidal mould oscillation was made. This research provided the test foundations and technical supports for studying the mechanical behavior of casting mould and optimizing the casting variables.

KEY WORDS: mould friction; measurement; non-sinusoidal oscillation; slab; continuous casting.

1. Introduction

The surface condition of the strand is an important aspect of continuous cast steel quality and it is mainly controlled by the initial stages of solidification in the mould.1–3) A good lubrication between the mould and strand shell is very important for the high productivity of the continuous casting and quality of its product. The lubrication is influenced by the properties of the mould powder but also by the friction forces caused by the periodic movements of mould and the descending strand shell. Moreover, inadequate powder consumption as well as a non-uniform lubrication may greatly affect the surface quality of the cast product.4)

The mould friction (MDF) between strand and mould is the most directly measurable parameter that can be used to describe strand/mould mechanical interaction and powder lubrication.5) It is therefore necessary to reduce the friction force between the mould and the solidified shell in order to avoid the formation of defects in the solidified shell. To enhance process monitoring to stabilize the operation and control casting defects, measurement of mould friction is very important for continuous casting process not only to detect product quality but also for the process optimization. Various research works had been published about this topic.1,4–9) However, few papers are devoted to research the periodical variation of mould friction, especially for the comparison of mould friction for sinusoidal and non-sinusoidal oscillation. In view of this, the investigation of intensive measurement was carried out to determine the friction forces at a slab caster. Details of this study are described in this paper.

2. Trial Description

The experiments were performed at the slab continuous caster with a slab strand size of 120 mm×1 000 mm and the extent of casting speed 0.5–2.6 m/min, and a thin slab strand size of 70 mm×1 000 mm and the extent of casting speed 1.0–3.5 m/min. The maximal amplitude and oscillating frequency of this caster are 5 mm and 400 cpm, respectively. The same steel grade (0.2% C) and powder were chosen in the series of trials. In order to apply the non-sinusoidal mould oscillation, a hydraulic-servo mould oscillation unit was installed in the caster machine instead of the mechanical type. The oscillator consists of two oscillating sets which locate symmetrically on both side of the mould platform, and the mould oscillation is assured by the leaf-spring guiding system. Typically, hydraulic oscillators use displacement transducers and pressure transducers in the hydraulic cylinders for feedback to the control system.

The working force (F, kN) namely the output force of hydraulic cylinder is calculated from the pressure difference between the inlet and outlet of the main hydraulic cylinder which supports mould assembly during oscillating by Eq. (1).

\[ F = P_{\text{inlet}} - P_{\text{outlet}} \]  

Where, \( P_{\text{inlet}} \) and \( P_{\text{outlet}} \) pressure of the inlet and outlet of the main hydraulic cylinder (kN), respectively.

The difference in working force of hydraulic oscillators between casting and no casting conditions at the same oscillating parameters represents the mould friction between
the mould and strand. As shown in Fig. 1, to characterize the non-sinusoidal oscillation mode a modification angle ($\alpha$) is introduced, which can be calculated by Eq. (2).

$$\alpha = \frac{t_1 - T}{4T} \times 360^\circ$$

Where, $T$: a oscillation period (s)
$t_1$: the moment of maximal displacement of non-sinusoidal oscillation (sec).

The sampling rate with 1 250 Hz was high enough for the measurement of at least 300 values for each oscillation period.

3. Result and Discussion

3.1. Periodic Mechanical Force on Shell Surface Caused by Mould Friction

Figure 2(a) shows the velocity and working forces of casing and no casting state at the same amplitude of 2.8 mm and oscillating frequency of 138 cpm, the casting speed is 1.26 m/min and the result of friction extraction is illustrated in the Fig. 2(b). The friction forces vary between $-15$ and $18$ kN following the mould oscillation. Since friction forces are depending on upward and downward movements within the mould-strand-system, the evaluation of the friction shows the typical change of pressure and tension. Maximum friction forces arise during the positive strip time of the rising mould, introducing tensions and cracks in the surface of the strand shell. On the other hand, lowest friction forces are generated by the descending mould within the negative strip time, leading to the healing of surface faults. During this period a healing of surface defects take place since the mould moves downwards and tensions in the surface area of the strand shell will be diminished or disappear. Following the motion of mould, the transition of mould friction takes places from tension to pressure or from pressure to tension during one oscillation period. To analyze the tensions or pressures acting on strand shell conveniently, the specific values of tensions or pressures within one oscillation cycle are defined in this work. As shown in Fig. 2(b), the maximal and average tensions are expressed as $\text{MDF}_\text{Max}$ and $\text{MDF}_\text{Ave}$, respectively. Similarly, $\text{MDF}_\text{Max(a)}$ and $\text{MDF}_\text{Ave(a)}$ (the absolute value of $\text{MDF}_\text{Max}$ and $\text{MDF}_\text{Ave}$) represent the maximal and average pressures acting on strand surface, respectively.

The average and maximal values of tensions and pressures obtained for stable casting are plotted in Fig. 3, and the oscillation conditions in Table 1 (I). It can be seen that the average values of tensions and pressures increase with the increment of their maximal values. $\text{MDF}_\text{Ave}$ is proportional to $\text{MDF}_\text{Max}$ and $\text{MDF}_\text{Ave(a)}$ is proportional to $\text{MDF}_\text{Max(a)}$. Irrespective of casting conditions, there is a substantially linear relationship between the average and the maximal values. In this case, both the average and the maximal values of tensions and pressures can express the tensile forces or compressive forces acting on solidified
3.2. Evolution of Shell Surface Force during the Whole Period of Casting

In the present work, an attempt to observe the variations of mould friction during the whole stage of casting was made. As an example, the evolution of the mould friction during the whole stage casting is measured, and MDF$_{\text{Max}}^{\text{H11001}}$ and MDF$_{\text{Max}}^{\text{H11002}}$ are calculated and plotted in Fig. 4, the oscillation conditions of which are shown in Table 1 (I). In initially several oscillation cycles, there exist tension and pressure acting on strand surface together. After that MDF$_{\text{Max}}^{\text{H11001}}$ and MDF$_{\text{Max}}^{\text{H11002}}$ begin to increase entering the phase without pressure, fluctuation of MDF$_{\text{Max}}^{\text{H11001}}$ and MDF$_{\text{Max}}^{\text{H11002}}$ is high. The situation where high friction levels are observed is during the start of the sequence. Although the casting speed reaches the operating value, the stabilization of mould friction demands a longer time. When the casting speed is changed, the thickness of the slag layer attached to the mould wall is also modified. As this process usually takes a period of time to be completed, lubrication and heat transfer in the mould are modified. Similar results have also been reported by other researchers.7) It should be also noted that there are no compressive forces appearing within the whole oscillation cycle. In other words, the solidified shell is suffering from tensile forces within the whole oscillation period, and this phenomenon will take a period of 5 min. There are no evident reasons which are found to explain this phenomenon, but the similar results are also observed in almost all the casting tests with high occurrence frequency. This may be related with the different powders used at beginning and normal casting processes. To some extent, high frequency of breakouts and surface defects during the start of a sequence may be related with the phenomenon of no pressures acting on strand surface.

After the casting speed increases continuously to a higher value, the tensile and compressive friction forces come forth acting alternately on strand surface, and the mould friction varies periodically along with the mould velocity within the range of $-15$ to $25$ kN. Finally, during the end of the cast, the slab tails are dragged from the mould at the casting speed of 1.0 m/min. Due to no more liquid steel poured into the mould, larger contraction producing thicker air gap promotes thicker slag layer, which might lead to lower friction values.

3.3. Effect of Casting Speed on Shell Surface Force

In order to observe the effect of casting speed on maximal tensile and compressive forces, the friction data in the sinusoidal oscillation mode are selected, as shown in Fig. 5 and the oscillation conditions in Table 1 (I). As the casting speed increases from 1.57 to 2.0 m/min, the value of maximal tensile force increases and the minimal compressive force decreases. The reasons for the variation of friction force are considered to be as follows: (1) An increment of casting speed results in the decrease of powder consumption, and therefore a decreased powder lubrication. (2) The maximal relative speed of the mould to the solidified shell in the positive strip time increases during the increase of casting speed, which leads to an increase in the tensile force. Accordingly, as the mould oscillation frequencies are directly proportional to the casting speed, the relative velocity during the negative strip time will decrease due to the combined effect of casting speed and frequency during the increase of casting speed. There is a lower relative velocity between mould and strand in negative strip time, and thus a lower compressive forces acting on solidified shell. To some extent, in order to obtain the proper effect of tensile and compressive force, it is suggested that the match relation between casting speed and frequency should be carefully considered, especially for high speed casting.

3.4. Comparison of Mould Friction at Sinusoidal and Non-sinusoidal Oscillation Mode

In this work, the measurements were also performed to investigate the effect of non-sinusoidal mould oscillation mode on the reduction of the mould friction. To compare the mould friction at the same operating parameters of casting speed, frequency and amplitude when using sinusoidal and non-sinusoidal oscillation mode, the periodical variation of mould friction was measured. Figure 6 demonstrate
the periodical variations of both mould velocity and mould friction at a casting speed of 1.67 m/min, the amplitude of 2.8 mm and frequency of 158 cpm. The non-sinusoidal modification angle was 10°. As can be seen from Fig. 6(a), the non-sinusoidal angle has a great impact on velocity waveforms as the velocity in positive strip time decreases and in negative strip time increases when non-sinusoidal oscillation mode is applied. This offers an oscillation movement where the time of upward motion of the mould is longer than that of downward motion in a single oscillation cycle.

In sinusoidal oscillation, the maximal tensile and compressive forces are 23.9 and 17.9 kN, respectively. While for non-sinusoidal oscillation, the maximal value of tensile and compressive forces are 20.9 and 19.2 kN. The maximal compressive forces of non-sinusoidal oscillation are bigger than that of sinusoidal oscillation, which is an important advantage of non-sinusoidal oscillation. The higher compressive force means the better effect to soldering surface crack and strand demould. The maximal tension of non-sinusoidal oscillation is lower than that of sinusoidal oscillation, which is due to the decrease of relative velocity, and is helpful to reduce the generation and expansion of crack. It should be also pointed out that, the healing time when the friction force is negative during non-sinusoidal oscillation, is longer than that of sinusoidal oscillation, and the former and latter are 0.118 and 0.114 s. At same time, the time of non-sinusoidal oscillation when friction force nears MDF-\text{Max} is longer than that of sinusoidal oscillation. In other words, non-sinusoidal oscillation can obtain better healing of surface defects, compared with the sinusoidal oscillation mode.

In this case, the features of non-sinusoidal mould oscillation in comparison with the sinusoidal mode are as follows. The relative speed of mould to the strand in positive strip period decreases, and accordingly the tensile force acting on the solidified shell is reduced. By comparison, the rela-

tive speed during the negative strip period increases, and the required level of the compressive force acting on the strand increases in the negative strip time.

The friction data during steady-state casting is selected and presented in Fig. 7, and the oscillation conditions of sinusoidal and non-sinusoidal mode are detailed in Table 1. In this trial, mould friction was measured under the same casting conditions, irrespective of casting speeds and oscillation mode. When casting speed is stable at 2.0 m/min in sinusoidal oscillation mode, the average tensile and compressive forces are 15.5 and 10.2 kN, respectively. Similarly, during the non-sinusoidal oscillation, the average tensile force is 16.2 kN and the compressive force is 11.1 kN. Although the tensile force of non-sinusoidal mode is a little greater than that of sinusoidal mode, a higher pressure is obtained when using non-sinusoidal oscillation mode. In addition, the ratio of pressures to tensions is 69% in non-sinusoidal mode, which is higher than that of sinusoidal mode. It is pointed out that the casting speed is 2.5 m/min during non-sinusoidal mode. It is concluded that for non-sinusoidal oscillation mode, a higher casting speed can be obtained and maintain at a stable level of tensions and pressures, compared with the sinusoidal oscillation mode.

3.5. Periodical Variations of Mould Friction before the Breakout

Figure 8 shows the periodical variations of mould friction during the normal state of start casting (a) and steady casting (b), hereinto, Fig. 8(a) is the data of thin slab casting with the casting speed 3.2 m/min and Fig. 8(b) is the data of slab casting with the casting speed 1.3 m/min. It can be seen that, although there are no compressive forces in the whole oscillation cycle during the start casting, the friction curves of normal state approximately change along with the mould velocity and fluctuate reposefully. Periodical variations of mould friction before breakout as two examples in thin slab casting are shown in Fig. 9, the casting speeds of which are 2.4 m/min (a) and 3.2 m/min (b), respectively. It is evident that the friction curves before the break are different to the normal curves. The trend of friction changing along with velocity is bad, and the friction curves fluctuate acutely, which means that the force acting on solidified shell is not steady, and the lubrication between the mould and strand shell is bad. Similar results have been gained by analyzing the friction of abnormal state of other dates. It indicates that abnormal fluctuation of friction would occur before the breakout. It also can be deduced
that when the trend of friction curves according with velocity curves is good, the lubrication between the mould and strand shell is steady; by contrast when the difference of two curves augments, it means to get the poorer lubrication effect, and the probability of bringing quality problems and abnormal state is increscent, relevant measures should be conducted in practical production.

4. Conclusions

The measurement of mould friction was carried out at a slab continuous caster, and a large quantity of mould friction data has been collected for subsequent analysis. The following results have been obtained.

1. Tensile and compressive friction forces acting on solidified shell appear alternative following the relative velocity between mould and strand. The maximal tensile forces are proportional to the average tensile force. Similarly, there is an underlying proportional relationship between the maximal compressive force and the average compressive force.

2. The phenomenon in which no compressive force acts on the strand is observed, and this will take a period time of several minutes after the start-up of casting sequence. It may be one of the main reasons that high frequency breakout occurs during the start of the casting sequence.

3. In this work, as the casting speed increases in the sinusoidal mould oscillation, the value of maximal tensile force increases and the minimal compressive force decreases.

4. Compared with the sinusoidal oscillation mode at the same casting conditions, the reduction of the relative velocity during positive strip time and the increment of relative speed in negative strip in non-sinusoidal oscillation mode will contribute to the decrease of tensile force and the increase of compressive force acting on strand shell. The casting speed of non-sinusoidal mode can reach a higher operating value than that of sinusoidal oscillation mode.

5. Abnormal fluctuation of friction would occur before the breakout. The trend of friction curves according with mould velocity curves can be used to estimate the lubrication effect between the mould and strand shell. When the trend is good, the lubrication is steady; contrarily it means the poor lubrication and abnormal state.

Acknowledgement

The authors would like to acknowledge the financial support of Special Processing of Raw Materials at Dalian University of Technology. The authors also thank Hu Junhong and Qin Bo for their kind help in conducting the plant trials in Baosteel Co.

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