Effect of Meniscus Thermal Barrier Coating Method on Mold Heat Transfer and Oscillation Mark Morphology of Cast Slabs (Postprint)

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Abstract

A novel method, designated as the Meniscus Thermal Barrier Coating Method (TBCMM), is proposed, which involves applying a thermal barrier coating above the mold meniscus to suppress heat transfer and thereby control the formation of oscillation marks on cast slabs. Using a test apparatus that simulates one-dimensional heat transfer at the mold meniscus, the influence of thermal barrier coating position on heat transfer was investigated, and the mechanism of oscillation mark suppression by the coating was analyzed. On a dip-type continuous casting simulator, simulated continuous casting experiments were performed with low-melting-point Sn-12.5%Pb alloy using molds with and without thermal barrier coatings, through which measured meniscus temperature fluctuation curves and cast slabs were obtained; comparative analysis of meniscus heat flux and cast slab surface oscillation mark morphology verified the effectiveness of the proposed TBCMM. Finally, on a pilot-scale continuous casting machine, the influence of thermal barrier coatings on the surface quality of steel continuous cast slabs was investigated, yielding steel cast slabs with reduced or even eliminated surface oscillation marks.

Full Text

Effect of Thermal Barrier Coatings Above Mould Meniscus on Mould Heat Transfer and Oscillation Mark Morphology of Strands

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Abstract

A novel method for inhibiting the formation of oscillation marks in continuous casting by applying thermal barrier coatings above the mold meniscus, referred to as the Thermal Barrier Coating above Mould Meniscus (TBCMM) method, is proposed. By suppressing heat transfer at the meniscus, this approach reduces temperature and heat flux fluctuations, thereby improving strand surface quality. Using a one-dimensional heat transfer testing apparatus that simulates mold meniscus conditions, the influence of thermal barrier coating location on heat transfer near the meniscus was investigated, and the mechanism by which the coating inhibits oscillation mark formation was analyzed. On a dip casting simulator, continuous casting experiments were conducted using low-melting-point Sn-12.5%Pb alloy with molds both with and without thermal barrier coatings. Measured meniscus temperature fluctuation curves and cast strands were obtained, and comparative analysis of meniscus heat flux and oscillation mark morphology confirmed the effectiveness of the proposed TBCMM method. Finally, pilot-scale continuous casting trials were performed to evaluate the effect of thermal barrier coatings on the surface quality of steel strands, producing cast billets with alleviated or even eliminated oscillation marks.

KEY WORDS thermal barrier coating, continuous casting, meniscus, oscillation mark

Introduction

Oscillation marks on continuous casting strand surfaces represent a typical quality defect in modern continuous casting production and constitute the root cause of numerous surface defects such as transverse cracks [1~6], significantly constraining both strand surface quality and the development of continuous casting technology. The mechanisms of oscillation mark formation and methods for their mitigation have long been focal points of academic research. Sengupta et al. [5] and Takeuchi et al. [6] observed that hook-type oscillation marks on slab surfaces are more prone to trapping inclusions and bubbles than depression-type marks, posing greater risks to strand surface quality. Through investigation of heat transfer characteristics at the mold meniscus, they identified that heat transfer at this location critically influences oscillation mark formation. Badri et al. [7,8] utilized a continuous casting simulation system to establish that heat flux at the mold meniscus correlates closely with oscillation mark formation positions, proposing a hypothesis based on abrupt heat flux changes for oscillation mark formation. Lei et al. [9] experimentally verified temperature fluctuations at the mold meniscus, proposing a hypothesis based on temperature fluctuations. Gu et al. [10,11] revealed the correspondence between abrupt heat flux changes and oscillation mark formation positions in low-melting-point SnPb alloy continuous casting. While these studies focused on formation mechanisms and explained the beneficial effects of technologies such as high-frequency small-amplitude oscillation, non-sinusoidal mold vibration, and mold flux modification on suppressing oscillation marks, none proposed an effective method for actively controlling heat transfer at the mold meniscus to inhibit oscillation mark formation, particularly hook-type marks.

This work proposes a novel method for suppressing oscillation mark formation, designated as the Thermal Barrier Coating above Mould Meniscus (TBCMM) method, which involves applying thermal barrier coatings above the mold meniscus to inhibit meniscus heat transfer and thereby control oscillation mark formation. The mechanism and effectiveness of this approach were thoroughly investigated. First, using a one-dimensional heat transfer testing apparatus simulating mold meniscus conditions, the influence of coating location on heat transfer was studied, and the mechanism of oscillation mark suppression was analyzed. Second, on a dip casting continuous casting simulator, Sn-12.5%Pb alloy continuous casting experiments were conducted using molds with and without thermal barrier coatings. Measured meniscus temperature fluctuation curves and cast strands were obtained, and comparative analysis of meniscus heat flux and oscillation mark morphology validated the effectiveness of the proposed TBCMM method. Finally, pilot-scale continuous casting trials were performed to evaluate the effect of thermal barrier coatings on steel strand surface quality.

1.1 One-Dimensional Heat Transfer Simulation Testing

Neglecting longitudinal heat transfer in the solidifying shell during continuous casting, heat transfer at the mold meniscus [10] can be simplified as one-dimensional. A schematic of the experimental apparatus is shown in [Figure 1: see original paper]. The apparatus comprises a Cu mold simulating the actual mold (with no thermal barrier coating on the surface), a power-adjustable infrared heat source, thermocouples embedded in the Cu mold, and a real-time data acquisition system. A preformed slag disk between the Cu mold and infrared source simulates the effect of mold flux on heat transfer in actual continuous casting.

During experiments, a constant 18 kW infrared heat source delivered steady heat flux to the Cu mold through the slag disk. After approximately 400 s of heating, the Cu mold temperature field reached steady state. Four thermocouples T1~T4 recorded real-time temperature data (four measurement points were used to improve reliability and accuracy). According to Fourier's law, the average heat flux q input from the infrared source to the Cu mold can be calculated as:

$$q := -1/3$$

where k is the thermal conductivity of the Cu mold, k=381 W/(m·K); d1, d2, and d3 are the distances between the four thermocouples, being 3, 5, and 5 mm respectively; T1~T4 are the temperatures at the corresponding thermocouples, in K.

Under identical experimental conditions, three additional Cu molds with thermal barrier coatings were fabricated, as schematically illustrated in [Figure 2: see original paper]. The configurations simulate: (a) hot-face coating on the mold inner wall, (b) cold-face coating covering the entire outer wall, and (c) meniscus coating applied to half the area on the water-cooled side at the bottom of the Cu mold, simulating localized coating at the mold meniscus on the outer wall.

During testing, the Cu mold in apparatus schematic [Figure 1: see original paper] was replaced with each of the three coated molds, yielding three additional sets of temperature-time curves. Correspondingly, three heat flux curves were calculated using Equation (1). By comparing the data obtained from the coated and uncoated configurations, the influence of thermal barrier coatings on mold heat transfer could be analyzed. Combined with the abrupt heat flux change hypothesis of oscillation mark formation [7,9], the mechanism by which the coating suppresses oscillation marks could be reasonably explained. In the experiments, the thicknesses of the preformed slag disk and thermal barrier coating were 4.0 mm and 0.5 mm, respectively, with thermal conductivities of 1.5 and 2.5 W/(m·K). Additional operational details can be found in references [10~16].

1.2 Dip Casting Experiments and Apparatus

Using a dip casting continuous casting simulator [7,8,17,18], a mold was designed as shown in [Figure 3: see original paper] for continuous casting experiments with low-melting-point Sn-12.5%Pb (mass fraction) alloy. Two experiments were conducted: the first using a mold without thermal barrier coating above the meniscus hot face, and the second with a thermal barrier coating applied above the mold meniscus (coating thickness and thermal conductivity of 0.5 mm and 2.5 W/(m·K), respectively).

Each experiment yielded real-time temperature data from two rows of embedded thermocouples in the Cu mold and cast strand samples. Based on temperature data from thermocouples at the same horizontal level, the average heat flux input to the mold was calculated using Equation (1), enabling comparative analysis of the coating's effect on meniscus heat transfer. Simultaneously, comparative observation and analysis of oscillation mark morphology on the cast strand samples elucidated the mechanism of oscillation mark suppression and validated the effectiveness of the proposed method.

1.3 Continuous Casting Experiments and Apparatus

Although Sn-12.5%Pb alloy can simulate the continuous casting process, significant differences from steel casting exist (for instance, silicone oil was used as mold flux in the apparatus shown in [Figure 3: see original paper]). Therefore, steel continuous casting experiments were conducted on a pilot caster using the mold design shown in [Figure 4: see original paper], where the thermal barrier coating covered the circumference at the mold meniscus on the outer wall (coating thickness and thermal conductivity of 0.5 mm and 2.5 $W/(m \cdot K)$, respectively).

Two casting trials were performed. In the first trial, the casting level was actively controlled such that during the first half of casting, the thermal barrier coating was positioned above the meniscus (bottom edge of coating flush with the liquid level); during the second half, the coating was positioned well above the meniscus. This allowed obtaining two different effects on the same strand: with coating (first half) and without coating (second half). In the first half, the coating bottom edge immersed into the steel melt during the mold's negative strip period, interacting with initial solidification; in the second half, the coating remained above the controlled level, not interacting with the initial shell. In the second trial, the casting level was precisely controlled to maintain the thermal barrier coating within the meniscus region throughout the entire casting process, ensuring continuous interaction with the initial shell. Analysis of oscillation mark morphology on the obtained strands revealed the mechanism of the coating's effect and validated the effectiveness of the proposed TBCMM method for actively controlling oscillation mark formation.

2.1 Effect of Meniscus Thermal Barrier Coating on Mold Heat Transfer

Four sets of real-time thermocouple data were obtained from the four Cu molds in [Figure 1: see original paper] and [Figure 2: see original paper] under 18 kW infrared radiation. [Figure 5: see original paper] shows the real-time temperature data from thermocouple T1 (located 2 mm from the Cu mold hot face) under different coating positions. [Figure 6: see original paper] presents the heat flux curves calculated from the real-time temperature data of thermocouples T1~T4 using Equation (1).

As shown in [Figure 5: see original paper], without thermal barrier coating, the temperature at 2 mm from the Cu mold hot face is approximately 473 K, close to actual mold wall temperatures in continuous casting production [19,20].

Similarly, [Figure 6: see original paper] shows a peak heat flux of 1.38 MW/m^2, also approaching actual mold heat transfer values [19,20], demonstrating the validity of the one-dimensional heat transfer apparatus for mold heat transfer studies.

[Figure 5: see original paper] also reveals that with cold-face coating, the temperature at 2 mm from the hot face approaches 673 K, exceeding the recrystallization temperature of actual mold materials [21], which is unacceptable in mold design. In practice, sacrificing the entire mold's cooling function by applying full cold-face coating is impossible; coating can only be applied locally at the meniscus, as shown in [Figure 5: see original paper], where the mold temperature remains below 573 K, not exceeding the recrystallization temperature. Compared with the uncoated condition, meniscus coating increases mold wall temperature by approximately 100 K. According to the abrupt heat flux change hypothesis of oscillation mark formation [7,9], higher temperatures at the mold meniscus significantly reduce the chilling effect on the initial shell, thereby suppressing oscillation mark formation.

[Figure 6: see original paper] shows that the maximum average heat flux for hot-face coating is approximately 1.22 MW/m^2, representing an 11.6% reduction compared with the uncoated Cu mold. The meniscus coating reduces input heat flux to approximately 1 MW/m^2, a 27.5% reduction.

Based on the extracted temperature data and corresponding average heat flux curves, and using material properties, the thermal resistance of the one-dimensional mold heat transfer can be analyzed using Equations (2) and (3):

where Rm is material thermal resistance, Rt is total mold resistance, d is material thickness, and l is material thermal conductivity. The calculation results are presented in , where interface resistance Ri is obtained by subtracting material resistance Rm from total resistance Rt. As shown in , interface resistance Ri dominates mold heat transfer in the one-dimensional experiments, accounting for 0.763~0.815 of Rt, consistent with Gu et al. [11]. Although the thermal barrier coating itself has small resistance, it increases overall mold resistance through interfacial interaction with the mold flux.

2.2 Effect of Meniscus Thermal Barrier Coating on Oscillation Mark Formation

Using the dip casting simulator shown in [Figure 3: see original paper], Sn-12.5%Pb alloy dip casting experiments were conducted with and without thermal barrier coatings. The casting temperatures were 240°C and 250°C, respectively, with vibration frequency of 1.333 Hz, amplitude of $±$3 mm, vibration velocity of 12.6 mm/s, and cooling water flow rate of 5.8 L/min.

[Figure 7: see original paper]a and b show the temperature variation curves measured by thermocouples embedded near the hot face of the Cu mold for experiments without and with thermal barrier coating, respectively. The numbers correspond to thermocouple positions from top to bottom in the Cu mold. Temperature curves from thermocouples farther from the hot face exhibit consistent patterns with slightly lower and more stable values, and are therefore not shown. Both sets of temperature curves follow the same five-stage pattern: heating-cooling-reheating-steady state-cooling, corresponding to mold immersion into the melt, 3~4 s pre-solidification, vibration initiation, normal casting, and casting termination. All measured temperatures with thermal barrier coating are lower than corresponding values without coating, indicating that the coating increases mold thermal resistance and reduces heat transfer from the melt to the mold. Conversely, the high thermal conductivity of the Cu mold plate results in significantly lower temperatures within the plate. [Figure 7: see original paper]a shows that thermocouples T3, T5, and T7 exhibit relatively high temperatures with certain fluctuations, characteristic of the meniscus region and close to the preset mold level, thus position T5 is taken as the meniscus location. In [Figure 7: see original paper]b, due to possible level deviation, position T13 is taken as the meniscus. [Figure 8: see original paper] presents two heat flux curves calculated using Equation (1) from temperature values at positions T5/T6 and T13/T14 from the two experiments.

The heat flux curves from the two dip casting experiments show significant differences. During steady-state casting, the average heat flux values without and with thermal barrier coating are 1.0 and 0.4 MW/m^2, respectively, representing a 60% reduction due to the coating—substantially greater than measured in the one-dimensional simulation ([Figure 6: see original paper]), attributable to the silicone oil mold flux used in the Sn-12.5%Pb alloy experiments. More importantly, the thermal barrier coating effectively suppressed the anticipated abrupt heat flux changes during casting. According to the abrupt heat flux change hypothesis [7,9], reduced heat flux change amplitude at the mold meniscus should suppress oscillation mark formation. [Figure 9: see original paper]a and b show the surface morphologies of strands obtained from dip casting experiments without and with thermal barrier coating, respectively. The strand in [Figure 9: see original paper]a exhibits obvious transverse stripes with average spacing d1 .5 mm, consistent with calculations using the formula (where vc is casting speed in mm/s and f is vibration frequency in Hz), indicating these are oscillation marks. In [Figure 9: see original paper]b, the transverse stripes have average spacing d2 15 mm, corresponding to the longitudinal dimension of the thermal barrier coating protrusion rather than oscillation marks. These results demonstrate that applying thermal barrier coating at the mold meniscus effectively suppresses oscillation mark formation, validating the effectiveness of the proposed TBCMM method for actively controlling meniscus heat transfer to inhibit oscillation marks.

2.3 Mechanism of Oscillation Mark Suppression by Meniscus Thermal Barrier Coating

The heat flux curves from the two Sn-12.5%Pb alloy dip casting experiments are plotted together with mold displacement and velocity curves in [Figure 10: see original paper], where the negative strip time (NST) of mold oscillation is marked by shaded regions. Without thermal barrier coating, heat flux always changes abruptly during NST, consistent with literature [7,17]. With thermal barrier coating, heat flux amplitude is significantly reduced, showing no abrupt change characteristics but rather regular fluctuations, demonstrating suppression of meniscus heat transfer.

According to the abrupt heat flux change hypothesis [7,9], heat flux changes occur during NST because the downward mold velocity exceeds casting speed, causing intense heat exchange between the relatively cold mold wall and the initial shell, rapid shell growth with increased mechanical strength, and inward bending deformation under downward mold vibration, while liquid metal overflows upward to form oscillation marks. Strong initial shells tend to form hook-type marks, whereas weaker shells form depression-type marks. In the proposed TBCMM method, the coating is positioned above the mold meniscus and oscillates with the mold. Its trajectory during one cycle is shown in [Figure 10: see original paper]a. At NST onset, the coating bottom begins to immerse into the melt, and interfacial heat exchange between the coating and initial shell is significantly reduced compared with that between the uncoated mold wall and shell. This reduces solidification strength of the initial shell, thereby suppressing oscillation mark formation or promoting depression-type rather than hook-type marks, consistent with the comparative results in [Figure 9: see original paper].

2.4 Effect of Meniscus Thermal Barrier Coating on Oscillation Mark Morphology of Steel Strands

To further investigate the effect of thermal barrier coatings on oscillation mark morphology and validate the effectiveness of the proposed TBCMM method, a thermal barrier coating mold for steel casting was designed ([Figure 4: see original paper]) and pilot-scale trials were conducted with low-carbon steel Q235B. Experimental conditions included: casting temperature of 1823 K, casting speed of 0.4 m/min, mold oscillation frequency of 1.217 Hz, amplitude of $±$3.5 mm, primary cooling water flow of 101.7 L/min, and secondary cooling water flow of 50 L/min.

Following the experimental method described in Section 1.3, the same mold was used with the thermal barrier coating applied above the meniscus on the mold outer wall. Two types of trials were conducted. In the first type, during the first half of casting, the coating bottom edge was flush with the liquid level, 70 mm from the mold top; during the second half, the coating was positioned well above the meniscus (steel surface 90 mm from mold top). In the second type, the coating bottom edge remained flush with the target level (70 mm from mold top) throughout the entire casting process, maintaining continuous interaction with the initial shell to obtain oscillation-mark-free strands.

Two strands from the two types of steel casting trials are shown in [Figure 11: see original paper]. [Figure 11: see original paper]a shows the low-carbon steel strand from the first trial type. Through active level control, when the level was high (70 mm from mold top), the coating was positioned above the meniscus (bottom edge flush with liquid level) and immersed into the steel melt during NST to interact with initial solidification, yielding a strand without obvious oscillation marks. When the level was low (90 mm from mold top), the coating remained above the controlled level without interacting with the initial shell, resulting in a strand surface with visible oscillation marks. [Figure 11: see original paper]b shows the strand from the second trial type, where precise level control (70 mm from mold top) maintained the coating within the meniscus region throughout casting, producing an oscillation-mark-free strand.

Comparison of strand surface morphologies from the two trial types demonstrates that applying thermal barrier coating at the mold meniscus effectively alleviates or eliminates oscillation mark formation on steel strands, further validating the effectiveness of the proposed TBCMM method for suppressing oscillation marks.

Conclusions

(1) Although the thermal resistance of meniscus thermal barrier coating represents a small fraction of total mold thermal resistance, it reduces mold heat flux by at least 27.5% and increases mold wall temperature. The coating increases overall mold resistance through interfacial interaction with mold flux.

(2) Oscillation mark morphology on low-melting-point Sn-12.5%Pb alloy strands demonstrates the effectiveness of the TBCMM method in suppressing oscillation marks. In steel continuous casting, applying thermal barrier coating at the meniscus effectively alleviates or eliminates surface oscillation marks on steel strands.

(3) The mechanism of oscillation mark suppression by meniscus thermal barrier coating involves effective reduction of temperature fluctuations and abrupt heat flux changes at the mold meniscus, thereby suppressing or weakening oscillation mark formation.

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