Effect of roller speed on heat transfer for ultra-thick steel plate during quenching

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Abstract. In order to clarify the effect of roller speed on the heat exchange characteristics for ultra-thick steel plate during cooling, the roller quenching experiment was completed with the variable roller speed in the range of 3.2-12.8 mm/s. The surface heat transfer conditions were obtained by inverse heat conduction, and used to study the effect of roller speed on the surface rewetting phenomenon and heat flux. It was found that the rewetting speed and rewetting temperature increased with the increase of roller speed, and a higher surface heat flux was reached. By comparing the maximum cooling speed at different temperature measured points, increasing the roller speed had a positive effect on increasing the cooling uniformity along the horizontal direction. However, the cooling difference along the thickness direction was enlarged. The above research results would provide method and basis for the technology optimization of roller quenching for ultra-thick steel plate.

1. Introduction

The goal of today's manufacturing industry is to obtain products with high strength, toughness, formability and weldability at reasonable cost. Ultra-thick steel plate is widely used in marine engineering, construction engineering, heavy machinery and other aspects [1]. With the increased infrastructure construction projects, the market demand for ultra-thick steel plate was gradually expanded [2]. Quenching with different heating and cooling systems can adjust the internal microstructure and improve the performance of steel plate [3-4]. Compared with that for thin and medium plate, the temperature field and stress field for ultra-thick plate are uneven during quenching due to the large thickness, which leads to the uneven shape and performance. Therefore, how to control the internal temperature field of ultra-thick plate by adjusting the cooling system is an important and difficult point for the quenching technology.

At present, the common quenching methods for ultra-thick plate mainly include immersion quenching and roller quenching. The former is to transfer the heated ultra-thick plate to the water tank, and speed up the heat exchange between the plate surface and coolant by stirring. However, due to the tank size and stirring conditions, the steel plate produced by immersion quenching has the low strength and poor cooling uniformity [5]. Roller quenching means that the steel plate is cooled in motion through the roller table, which would been affected by the water flow, nozzle arrangement, roller speed and other parameters. The cooling uniformity and cooling speed are controllable. However, the different time for the steel plate entering the quenching machine leads to the difference performance between the head and tail of the plate. In addition, the long quenching expands the influence of the roller speed on the heat exchange process, especially for the ultra-thick plate. The existing research on the influence of roller speed on heat transfer mainly focused on the surface heat transfer efficiency [6] or the internal heat
conduction law [7-8], but less on the rewetting phenomenon. Generally, the effective heat transfer occurred after rewetting, so the related research is important.

In this study, instead of 100 mm thick plate, 50 mm thick plate was used to complete the half thickness roller quenching experiment and the roller speed was 3.2-12.8 mm/s. According to the experimental data, the rewetting phenomenon, surface heat transfer mechanism and internal heat conduction were studied and the result would provide method and basis for the technology optimization of roller quenching for ultra-thick steel plate.

2. Experimental material and method
The experimental material was 150 (length) × 100 (width) × 50 (thickness) mm AISI304 austenitic stainless steel. The holes used to install the thermocouples were 3-47 mm away from the cooled surface, and the depth was 50 mm, as shown in Fig. 1, where, r was the horizontal distance between other points and the first cooled point, and h was the vertical distance between the point and the cooled surface. The nozzles were arranged in-line with the diameter of 3 mm and the spacing of 25 mm. The jet height was 150 mm, nozzle outlet velocity was 1.1 m/s and the roller speed \( V_p \) was 3.2, 6.4, 9.6 and 12.8 mm/s respectively. One end of the embedded thermocouple was inserted into the temperature measured hole, and the other end was connected with the temperature recorder (GL840). During the experiment, the steel plate was heated to 900 °C in the resistance furnace, and then quenched at different \( V_p \). The high alumina refractory brick was placed under the test plate to make the lower surface of the steel plate as adiabatic as possible. Therefore, the 50 mm thick plate could replace the upper half of the 100 mm ultra-thick plate to complete the roller quenching experiment, and the data could be used to study the effect of roller speed on heat exchange process from the surface to the core of the ultra-thick plate.

![Fig. 1. Experimental process.](image)

Since the thermal boundary conditions could not be obtained directly, the inverse heat conduction method was used to calculate the surface temperature and heat flux [9]. The temperature history used in the calculation was the points at \( h = 3 \) mm. In the cooling process, the temperature drop at \( h = 3 \) mm was mainly caused by the heat exchange along the thickness direction, rather than that along the horizontal and width directions. Therefore, one-dimensional temperature field could be used for modeling and finite difference method was used for solving. The heat flux correction method used in the study was proposed by Gu et al. [10].
3. Results and discussion

3.1. Effect of roller speed on rewetting phenomenon

Fig. 2 shows the changes of fluid and thermal phenomena on the cooled surface when \( V_p = 3.2 \) and 12.8 mm/s. In this paper, when the surface of steel plate changed from dry state to alternate dry and wet state (the structure changed from film boiling to transition boiling, and heat flux increased explosively), rewetting phenomenon occurred. The upper surface points corresponding to P1-1, P1-2 and P1-3 were marked as P0-1, P0-2 and P0-3, and it was assumed that P0-1 was rewetted at \( t = 0 \) s. The influence range of each jet was a circular area with jet point as the center and jet spacing as the diameter. At the intersection of the jets, the fluid from different directions continuously accumulated and discharged, forming the cross flow [11]. According to Fig. 2(a), multiple streams of water could be observed above the dry region. When the surface temperature was higher than the Leidenfrost temperature, the fluid glided over the vapor film, and when the surface temperature was lower than the value, strong boiling from coolant was observed due to the broken vapor film.

When \( V_p = 3.2 \) mm/s, the contact time between the surface and cross flow was longer before the jet arrived, and the rewetting phenomenon could be observed. At \( t = 0.0 \) and 3.8 s, the color of the wall below the cross flow became dark and a large number of boiling bubbles were observed. When \( t \geq 6.7 \) s, some region was completely wetted, and the wetting front moved along the width direction of the steel plate. The fluid in the jet zone contacts the wall for a long time. Therefore, boiling bubble fully extracted the wall heat and grew up, which could be observed in the jet gap, as shown in Fig. 2(a).

When \( V_p = 12.8 \) mm/s, the contact time between the surface and the discharged cross flow was short compared with that at \( V_p = 3.2 \) mm/s before the jet arrived, and the surface was always dry. After being cooled by the first row-jet, the wall was still at a high temperature, which was conducive to accelerating the nucleation of boiling bubbles. The water temperature around the bubble decreased rapidly due to the high \( V_p \), and the bubble broke in a tiny size. No obvious boiling bubble was observed in Fig. 2(b).
Fig. 3. Rewetting region distribution (a) $V_p=3.2$ mm/s (b) $V_p=12.8$ mm/s.

Fig. 3 shows the rewetting region distribution on the surface from P0-1 to P0-3. When $V_p = 3.2$ mm/s, with the moving steel plate, P0-1 and P0-2 were rewetted in turn, and the width of wetting front increased. When $t = 6.7$ s, the wetting front extended to P0-3, and P0-1 had been completely wetted. Afterwards, with the decreased wall temperature, the complete wetting area increased and rewetting area decreased. The wetting front width was $[12.5,25)$ mm. When $V_p = 12.8$ mm/s, rewetting occurred on the all studied region at $t = 1.9$ s, and the wetting front width was supposed to be $\geq 25$ mm. Therefore, it could be considered that with the increase of $V_p$, the surface area contacting with the coolant intermittently in unit time increased, resulting in the increased wetting front width and the decreased rewetting time.

Fig. 4. Rewetting parameter (a) rewetting time (b) rewetting temperature (c) duration in the transition boiling.
Fig. 4 (a)-(b) shows the rewetting time $t_{rew}$ and rewetting temperature $T_{rew}$ at P0-1, P0-2 and P0-3 when $V_p = 3.2-12.8$ mm/s. Due to the plate moving direction, $t_{rew}$ from P0-1 to P0-3 increased in turn. When $V_p = 3.2, 6.4, 9.6$ and 12.8 mm/s, the rewetting speed from P-1 to P0-3 was 3.5, 6.8, 10.3 and 13.1 mm/s respectively, which was about the sum of roller speed and wetting front spreading velocity (according to Hatta et al. [12], the wetting front would spontaneously expand the non rewetting region due to the radial temperature gradient). According to the above results, the roller speed was the main influencing factor for rewetting speed. When different $V_p$ was used, $T_{rew}$ difference at P0-1 was not more than 5.7 °C, as shown in Fig. 4(b). The above result indicated that the effect of initial cooling temperature was basically eliminated through experimental operation, and the data could accurately reflect the change of rewetting and heat transfer behavior under different roller speed.

The dry surface continuously radiated heat to the environment, and the roller speed would determine the duration of the above process. When $V_p$ increased from 3.2 to 12.8 mm/s, $T_{rew}$ at P0-2 and P0-3 increased by 12.4 °C and 16.5 °C respectively, which indicated that the increased roller speed could promote the wall to contact with coolant directly at higher temperature. Moreover, the high-temperature surface had a positive effect on accelerating the boiling bubble circulation frequency and improving the wall heat transfer intensity (according to Lu et al. [13], heat was mainly transferred to the fluid through forced convection and bubble circulation). The transition boiling durations at different positions are shown in Fig. 4 (c). It could be found that the surface was still in the transition boiling structure after passing through the first row-jet, which was consistent with the observation in Fig. 2. With the increase of $V_p$, the velocity of the fluid relative to the wall increased, which leads to the enhancement of the ability for the fluid to scour the boiling bubbles and the improvement of the heat transfer efficiency in the transition boiling. The results showed that when $V_p$ increased from 3.2 to 6.4, 9.6 and 12.8 mm/s, the average surface temperature drop speed in the transition boiling increased by 38.7%, 73.0% and 84.1%, respectively.

3.2 Effect of roller speed on heat transfer efficiency

![Fig. 5. Heat transfer efficiency (a) maximum heat flux (b) Slope for the transition boiling (c) maximum cool speed.](image)
Fig. 5(a) shows the distribution of the maximum heat flux \( q_{\text{max}} \), and the value increased with the increased \( V_p \). When \( V_p \) increased from 3.2 mm/s to 12.8 mm/s, \( q_{\text{max}} \) increased by 3.0% at P0-1, which proved that the cooling efficiency could be improved by increasing the heat convection intensity in the transition boiling structure. After that, \( q_{\text{max}} \) increased by 15.6% at P0-3. The reason was that the higher \( T_{\text{rew}} \) increased the nucleation density and circulation frequency of boiling bubbles, which further enhanced the heat transfer. Many scholars reported that the slope of transition boiling was a fixed value within the error range in the boiling curve (i.e., the curve of heat flux versus wall superheat), and Nobari et al. [14] thought that the value was about 0.044. The above conclusion was obtained when the thin plate was taken as the research object. In this study, the slope is shown in Fig. 5(b), which increased with the increased roller speed and rewetting temperature. This might be due to the fact that when the surface was rewetted, the high-temperature part would continue to transfer heat to the low-temperature part along the thickness, which led to the prolongation of the transition boiling duration, and the enhancement of the sensitivity of the transition boiling to the thermal boundary conditions.

Fig. 5(c) shows the distribution of the maximum cooling speed \( v_{\text{max}} \) at different temperature measured points, which is similar to that of \( q_{\text{max}} \) [15]. During the cooling, the surface temperature was lower than that inside. The heat was transferred from the high-temperature part to the low-temperature part due to the temperature gradient, and \( v_{\text{max}} \) decreased with the increase of the distance from the cooled surface. When \( V_p = 12.8 \) mm/s, the maximum \( v_{\text{max}} \) could be reached at all points, compared with others. Along the horizontal direction, the \( v_{\text{max}} \) distribution was related to the contact time between the surface and the coolant. When \( V_p = 3.2 \) mm/s, there was a long period of radiation heat transfer on the surface before cooling by jet, and the surface temperature continued to decrease. The cooling efficiency were low at the position where the jet arrived late due to the low-temperature surface. With \( v_{\text{max}} \) moving from P0-1 to P0-3, the \( t_{\text{rew}} \) increased by 6.7 s, and the \( T_{\text{rew}} \) decreased by 22.6 °C. As a result, \( v_{\text{max}} \) difference along the horizontal direction at \( h = 3 \) mm was 22.78 °C / s, and the worst cooling uniformity was obtained compared with others. When \( V_p = 12.8 \) mm/s, the whole experimental area was rewetted within 1.9 s. Similar rewetting conditions at different surface positions led to small \( v_{\text{max}} \) difference and increased horizontal cooling uniformity. As shown in Fig. 4(c), affected by the heat conduction along the horizontal, the \( v_{\text{max}} \) difference at \( h = 47 \) mm was less than that at \( h = 3 \) mm. With the increased \( V_p \), at \( r = 0, 15 \) and 30 mm, the \( v_{\text{max}} \) difference along the thickness increased from 78.5, 65.6 and 56.2 °C / s to 83.1, 75.2 and 69.16 °C / s respectively, which indicated the decrease of thickness cooling uniformity caused by the limited heat conduction.

4. Conclusion
Using 50 mm plate with lower surface insulation, the half thickness roller quenching experiment was completed, and the roller speed was adjusted in the range of 3.2-12.8 mm/s. When the roller speed was increased, the rewetting time was shortened, and the wetting front width was increased. The slope of transition boiling in the boiling curve increased with the increased roller speed and rewetting temperature, which proved the influence of surface heat convection intensity and bubble circulation frequency on the transition boiling. The increased roller speed improved water volume in contact with the wall in unit time, and the surface heat flux and cooling speed at all temperature measured points increased. In addition, an increase in horizontal cooling uniformity and a decrease in thick cooling uniformity were observed.

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