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The influential factor studies on the cooling rate of roller quenching for ultra heavy plate

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HIGHLIGHTS

- Heat transfer coefficient is very high in high-pressure section.
- Temperature gradient remains unchanged in norm-pressure section.
- Water temperature and roll speed affect the cooling rate.
- The minimum cooling rate occurs in the depth of a quarter of thickness.

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ABSTRACT

The influences of water temperature and roll speed on the cooling rate in thickness direction of ultra heavy plate are experimentally investigated in the present work. The results indicate that the water temperature and roll speed have influences on total heat transfer coefficient and heat transfer type near surface of plate, and affect the cooling rate in thickness direction by changing temperature gradient distribution. The cooling rate in thickness direction decreases as the water temperature and roll speed increase, and the decreasing range of cooling rate has relations with cooling region, cooling intensity, quenching time, and thermal conductivity of plate.

1. Introduction

The ultra heavy plate is widely used in petrochemical, ocean engineering, construction machinery, power industry, etc. In order to obtain a better performance of steel plate, it is necessary to change the structure of steel through heat treatment under different heating temperature and cooling rate conditions [1–3]. The quenching of ultra heavy plate is divided into two types: immersion type and roller type. In the former type, the plate is cooled rapidly by stirring the water in cooling pool. Since the velocity of water is limited by the size of cooling pool, the cooling intensity of immersion type is lower in contrast to wall jet, and the cooling intensity is unevenly distributed in the plate for the different velocity of water. Besides, water temperature changes irregularly, so the quenching stability is pool in different batches of steel plate. The steel plate is transported into the quenching zone using roller in the roller quenching, and the plate is quenched in the movement. In comparison with immersion quenching, roller quenching has better uniformity, higher repetition rate, and the process is controllable, so the roller quenching gradually becomes the first choice of quenching type for ultra heavy plate [4].

In roller quenching, the cooling rate could visually reflect the temperature drop and the uniformity of cooling in thickness direction, which is vital for the microstructure evolution and performance tuning of steel plate [5]. However, the quenching test is very intricate and the temperature drop measurement in thickness direction is very difficult, so the studies on the influential factors of wall jet impingement heat transfer and thermal conduction for ultra heavy plate are very few. Ishigai et al. [6] investigated jet impingement heat transfer for plate temperatures up to 1027 °C. Characteristic points of the boiling curve were shifted to higher heat fluxes and wall temperatures when jet velocity were increased. Zhou et al. [7] conducted the study on the surface heat transfer properties of plate in immersion quenching process, which demonstrated the relations of temperature drop of plate and

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Nomenclature

B	the width of steel plate (m)
B_{io}	Biot number at top surface
B_{iD}	Biot number at bottom surface
$C(T)$	specific heat of plate (J/kg °C)
C_{dn}	influential function (W)
H	The thickness of steel plate (mm)
h	surface heat transfer coefficient (W/m^2 °C)
q_x	heat flux in thickness direction (W/m^2)
q_y	heat flux in width direction (W/m^2)
t	temperature (°C)
t_h	temperature in thickness direction (°C)
t_B	temperature in width direction (°C)
t_∞	water temperature (°C)
t_B	temperature in width direction (°C)
T_0	surface temperature of plate (°C)
T_w	water temperature (°C)
Δt	temperature difference (°C)
v	roller speed (m/min)
w	water quantity (m^3/h)

Greek symbols

λ	(t) Thermal conductivity (W/m °C)
ρ	density (kg/m^3)
τ	time (s)
$\varphi(t)$	heat capacity (W)

Subscripts

h	thickness direction
B	width direction

cooling rate with surface temperature. Zeitoun [9] employed visualization method to measure the hydraulic jump radius of jet impingement, and investigated the influences of jet distance, nozzle type, jet flow rate etc. on the surface heat transfer. However, the existing researches were limited to a certain experimental conditions and specimen size, mainly focused on the effects of cooling conditions on the surface heat transfer of plate, did not refer to the inner thermal conduction of plate, and discussed little on the relations of cooling rate and cooling parameters. In addition, the existing literature mainly discussed the cooling of plate at rest, did not further analyze the influences of wall jet flow configuration on heat transfer zone in movement of plate.

In the present work, the surface convection heat transfer and the inner thermal conduction of ultra heavy plate are investigated experimentally under jet impingement condition, the mathematic model of the roller quenching is established, and the influences of water temperature and roll speed on the cooling rate in the thickness direction are analyzed under different cooling conditions.

2. Experimental materials and method

2.1. Materials and devices

The experimental plate is the high-strength rolling plate which is used for oil tank, its chemical constituents are (mass fraction): 8% C, 24% Si, 1.54% Mn, ≤0.6% P, ≤0.2% S, ≤2.6% Nb, ≤4.1% V, ≤1.4% Ti, 21% Mo, 23% Ni. The size of steel plate is 160 mm × 350 mm × 500 mm.

The temperature changes in the quenching process is monitored and recorded by the thermocouple (WRKKT4-171). One end of the thermocouple is inserted into the plate in the thickness direction (depth of 80 mm), the other end is connected with Temperature Recorder (sampling period of 0.2 s). The roller quenching is conducted after the plate is heated to the desired temperature. The experimental devices are shown in Fig. 1, and the structure parameters are illustrated in Fig. 2. The effective width is 470 mm, effective length is 10 m. The device is divided into high- and norm-pressure cooling sections, and the water jet pressures are 0.8 MPa and 0.5 MPa respectively. The length of high-pressure section is 4.8 m, there are many kinds of jet nozzles in the high-pressure section, and the maximum instantaneous flow is 1000 m^3/h, so the surface temperature of plate can be cooled rapidly to form the larger temperature gradient in the thickness direction. There are multi-rows of round jet nozzles in the norm-pressure section, and the maximum instantaneous flow is 1500 m^3/h. On one hand the temperature gradient in the thickness direction is kept, on the other hand the surface temperature of plate can not be lowered overly, so the temperature difference between the surface of plate and the cooling media is maintained to exchange heat [10]. The roller can be adjusted accurately in the roll speed of 0.5 m/min to 3.5 m/min.

The temperature of steel plate is monitored by thermocouple (WRKKT4-171) and recorded by temperature recorder (SMT-14-3000-1250-K) during heating and quenching processes [11]. The measuring points of thermocouples are shown in Fig. 3, the temperature sensing location near surface is P1, the temperature sensing location at one-quarter thickness is P2, and the temperature sensing location at half thickness is P3. The temperature in the other area of steel plate is obtained through calculation. The quenching process for heavy steel plate is shown in Fig. 4. Water is provided to jet nozzles by high- and norm-pressure pumps at fixed flow rate and pressure. The flow rate is controlled by control valve, and the control valve and flow meter constitute a closed loop control system. The jet nozzles are controlled by block valve, and

Fig. 1. Test apparatus and the internal structure of normal pressure section.