Experimental Study of Laminar Cooling Process on Temperature Field of the Heavy Plate

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Abstract. Laminar cooling is the key to hot rolling and controlled cooling. It can improve the performance of steel by changing the grain transformation. The key to improve product quality is that the laminar cooling process model can calculate the cooling strategy accurately. The conventional empirical formula calculation method can’t guarantee the accuracy of the water cooling heat transfer coefficient, which is the critical parameters of laminar cooling process. Therefore, an experimental study like this is needed. In this paper, the temperature measurement experiment of laminar cooling is carried out by the method of experimental temperature measurement. The experimental design stage uses COMSOL software to simulate the temperature field temperature to determine the diameter and depth of the measurement. Then the laminar cooling experiment is carried out and collects the temperature measurement data under different conditions. The error of the measured temperature field is less than 0.1% under the final experimental conditions. The heat transfer coefficient is obtained by experimental data and input in heat transfer model, the surface temperature is calculated, and the temperature is compared with the experimental data, the relative error is less than 20℃.

1. Introduction
Laminar cooling process is the last important process in hot rolling production, which directly determines the final quality of the product [1, 2, 3]. The key to improve the laminar cooling process is to calculate the critical parameter – the water cooling heat transfer coefficient, however, there are a lot of difficulties to solve it directly [4, 5]. Solving the heat transfer coefficient is based on the temperature test experiment [6, 7]. Reasonable experimental scheme and detailed study of the embedding technique is in order to ensure the accuracy of the experimental data.

The experimental design and experimental research of laminar cooling process for the heavy plate are introduced in this paper. First, the experimental platform according to the need of experiment is built. The temperature field is simulated by COMSOL software and the punching plan is designed. Then experiment is carried out and the experimental data is analyzed.
2. Experimental method of temperature measurement

2.1. Experimental Foundational Principle

The temperature measurement experiment is to obtain the temperature variations of several points in internal plate in the cooling process after hot rolling. Owing to the complexity of the heat transfer mechanism between the heavy plate surface and the cooling water, the characteristics of cooling process vary with time [8]. And due to the disturbance of water vapor and oxide on billet surface, it is difficult to ensure the accuracy of the temperature measurement data. Therefore, the method of measuring temperature in the internal plates is used [9].

In this experiment, the method of unsteady-state experiment is adopted. Heat the plate samples to 800℃ and retain heat for 30 minutes, move billet to laminar cooling platform, install the temperature measuring device, and measure the temperature drop values of three points inside the heavy plate. The temperature distribution in the heavy plate in different working conditions is measured by experiments, in order to provide data for the following research on laminar cooling process of the heavy plate.

2.2. Experimental Platform

In order to meet the experimental requirement, transient temperature of several points inside the heavy plate in a high temperature is measured. Fig.1 shows the experimental platform system. The experimental platform for the laminar cooling system consists of a high-temperature chamber electric furnace, steel plate specimen, roller tables, spray device and temperature measuring device.

The box-type high-temperature resistance furnace is used to heat samples, and then the temperature measuring thermocouples are installed in sample, which is sent into the experimental platform for laminar cooling. Fig.2 shows the laminar cooling experimental equipment.

\[\text{Figure 1. The experimental system schematic.}\]

\[\text{Figure 2. The laminar cooling experimental equipment.}\]
2.3. Improvement of Temperature Measurement Position

In order to study the effect of embedding thermocouples into the plate on the heat transfer property, with the condition that the convective heat transfer coefficient is given, COMSOL software is used to simulate cooling process in the same conditions before and after its drilling.

The water cooling process is a relatively complex process, and the heat transfer coefficient of this process uses the empirical formula as (1) in the literature [10]:

\[
h_w = \frac{9.72 \times 10^5 \times \omega^2 \times D^3}{(T_{SU} - T_w) \times P_L \times P_C} \times 1.163
\]

(1)

Where, \( \omega \) (L/(min\cdot m^2)) is water density; \( D \) (m) is diameter of injectors; \( T_{SU} \) (°C) is surface temperature and \( T_w \) (°C) is water temperature; \( P_L \) (m) is nozzle spacing in the direction of the rolling line and \( P_C \) (m) is nozzle spacing in the vertical direction. According to the experiment, \( \omega \) is 300 L/(min\cdot m^2), \( D \) is 0.01 m, \( T_w \) is 30°C, \( P_L \) is 0.45 m and \( P_C \) is 0.04 m.

In the model, the parameters are set according to the above set, the model is calculated by 60 seconds, and the data are extracted. Taking the center point as an example, the model of the insertion of a thermocouple after a perforation is compared with that of a nonpunching model as shown in Fig.3.

Fig.3 shows that when the temperature thermocouple is inserted into the hole, at first the heat exchange reaches a balance, and the temperature drop gradually tends to consist with the original temperature field with the increase of time, the final deference is within 0.1°C. It indicates that as time goes on, the temperature disturbance can be negligible due to the insertion of temperature measuring device. It shows that the scheme is feasible.

![Figure 3. Comparison of temperature drop before and after thermocouple in central measuring point.](image)

In order to protect the temperature field structure of the heavy plate, the number of temperature measurement points should be as small as possible. COMSOL is used to calculate two kinds of conditions and obtain two kinds of varieties of temperature with time.

The strategy adopted in this experiment is to set up a temperature measuring point in the location of the center of the section, and set up a temperature measuring point on the upper and lower sides symmetrical positions. As shown in Fig. 3, the locations of the temperature measurement points are A, B and C. The size is 300* 30mm^2, the distance between the upper side and point A is 5mm, and the lower side and point C is the same distance. The distance between two points is 10mm.
Using COMSOL Multiphysics for simulation, the temperature field is as shown in Fig. 4. At the same time, a temperature field without measuring points but with the same parameters is built. The different data between the two models is compared by the domain point probe method.

Considering the vertical punching, distance between two holes in the direction of thickness is too close that leads to excessive temperature loss. The simulation is carried about the relationship between distance of holes and the loss of temperature. The simulation results show that the temperature field of each hole is basically unchanged when the hole distance is above 8mm, and there is no effect on each other. The above vertical hole drilling scheme is too close to damage the temperature field. Therefore, the scheme is improved.

In district with same flow density, the hole distance is increased as much as possible, so the symmetrical distribution can be used. The upper hole and the lower hole are set in the skew symmetrical position of the central axis respectively, in order to reduce the influence caused by pitch of holes. The point positions are shown in Fig. 6. The specific model established by COMSOL is shown in Fig. 7.
Figure 7. Program for diagonally placing thermocouples.

The temperature data at the temperature measurement point of the above model and the original temperature field are extracted. Three temperature measurement points are compared with two kinds of buried scheme. The Fig.8 shows that when thermocouple is inserted into the measuring hole, the temperature disturbance caused by the insertion of the temperature measuring device can be eliminated as time goes on, and it will achieve the same accuracy as the original temperature field, so the scheme is feasible.

Figure 8. Comparison of temperature drop before and after installation of thermocouples.

The specific data to reach the temperature range is shown in Table 1. Compared with the vertical buried couple scheme, the time required of the symmetrical buried couple to meet the accuracy requirement is shorter. Therefore, the symmetrical buried couple scheme is applied to the locations of thermocouples in this experiment.

Table 1. The time required for two model temperature difference points to meet the error accuracy.

| Punching scheme             | Temperature (℃) |   |   |
|-----------------------------|-----------------|--|--|
|                             | Point A | Point B | Point C |
| Vertical arrangement        | 18.4     | 18.6    | 19.1    |
| Skew symmetry arrangement   | 5.0      | 14.2    | 6.4     |

The simulation analysis is carried out with COMSOL software. Taking the water cooling process as an example, the results show that the error requirements can meet within 15s after installation, and the error between the experimental temperature field and the original temperature field is within 0.1℃ as time goes on, which is consistent with the experimental requirements.
3. Experimental process
The high-temperature resistance furnace is used to heat the steel plate sample to the preset temperature until the temperature difference between the upper and lower surfaces of the plate is stable. Move the steel plate sample to the preset position under the nozzle. The thermocouples are inserted into the plate sample and connected to ADAM-4018 temperature acquisition equipment, thermocouples can continuously record the temperature change processes during the cooling process of the plate. The water retaining device should be adopted in order to prevent the cooling water from short circuiting of the thermocouple and influence the accuracy of the experimental results.

4. Experimental results and analysis
After laminar cooling, the difference in temperature of the heavy plate between surface and center leads to the internal heat conduct to the surface.

Using thermocouples to collect the temperatures of the measure points in experiment, the plate the temperature variety in the whole process of air cooling and water cooling can be obtained. The temperature drop curves of the billet are shown in the Fig. 9.

![Figure 9. The cooling data in experiment.](image)

1) With the increase of the thickness of the billet, the temperature gradient between the surface and the center is increased. The temperature drop of center point decreases with the increase of billet thickness. With the increase of the thickness of the billet, the longer it takes to reach the uniform temperature distribution.

2) At the beginning of water cooling, the temperature of the upper and lower points is reduced rapidly, the change of the temperature of the center point is small, and the temperature gradient of the cooling is gradually increased. This is due to the internal thermal resistance of the billet, the thermal disturbance of the external cooling water cannot through deep quickly, and the internal heat cannot be transmitted to the surface quickly, resulting in a large temperature difference between the surface and the center. The greater the flow density is, the faster the cooling rate is, the greater the convection heat transfer coefficient is.

3) As the cooling time increases, the difference in temperature between the surface and the center increases. The difference between surface and center is up to 114.5°C when cooling time is 10 seconds, while the difference is up to 191.8°C when cooling time is 20 seconds. The corresponding re-reddening time is longer, the final temperature is lower before straightening.

4) In the experiment, the thermoelectric couple should be used as much as possible, and the diameter of the protective tube is small. Because of the existence of measurement lag, the amplitude of the temperature fluctuation detected by the thermocouple is smaller than the amplitude of the actual fluctuation. In order to measure the temperature accurately, a thermocouple with a small time constant should be selected. In order to reduce the time constant, in addition to increasing the heat transfer coefficient, the most effective way is to minimize the size of the hot side. Since the temperature should
not be used without the protection, the armored thermocouple with a diameter of 3mm is selected. The temperature measurement point curve after the installation of thermocouples is shown in Fig. 10.

**Figure 10.** Response characteristic curves of thermocouples at different locations.

5. **Conclusion**

According to the experimental study and the application of the process, thickness, flow density and water cooling time have influence on the temperature field of the heavy plate, the following conclusions can be drawn:

1) The cooling time of uniform is directly proportional to the thickness of the heavy plate.
2) The convective heat transfer coefficient increases with flow density.
3) With the re-reddening time increases, the temperature will decrease before straightening.

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