NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 111 MARCH 2016

Technical Report

UDC 621 . 771 . 237 . 016 . 2 : 536 . 53

Temperature Measurement Technology in Water Cooling Process and High Accuracy Cooling Control Technology for High Tensile Hot Rolled Strip

Tatsuro HONDA* Shigemasa NAKAGAWA
Hisayoshi TACHIBANA Chihiro UEMATSU
Yasuhiko BUEI Koichi SAKAGAMI

Abstract

Although there is a clear necessity to reduce CO_2 emissions from industrial activities, a stable supply of high-strength and high-functionality steel sheets is nevertheless required for automotive use. To manufacture high-strength steel sheets on a hot strip mill, it is necessary to precisely control the steel temperature in the cooling process between finishing rolling and coiling, but high-accuracy cooling control is not easy in this low temperature range. To solve this problem, Nippon Steel & Sumitomo Metal Corporation has developed a new type of pyrometer to measure the strip temperature stably during cooling on the hot run table of a hot strip mill and a control process for precise cooling of the strips using the pyrometer. The new strip cooling process was developed and put into commercial practice at Kashima Works and is being expanded to other mills of the company.

1. Introduction

Nippon Steel & Sumitomo Metal Corporation has devised and implemented various measures to reduce the contribution of its works to global warming. In its R&D activities in the fields of process monitoring and rolling operation control, the company has always emphasized decreasing the amount of CO_2 emissions. High fuel efficiency is required for automobiles, and, at the same time, the social need for higher collision safety is ever more urgent. To meet these requirements, the use of high-tensile steel sheets in automobiles is rapidly increasing.

Steel sheets for automotive use are produced mostly using hot strip mills. At the start of this development study in 2000, high-tensile steels accounted for roughly 40% of the production of the Hot Strip Mill Plant of the Kashima Works, but it has increased to as much as 60% in recent years. The strength of the steels rolled is also becoming increasingly higher. High-tensile steels are manufactured to the desired mechanical properties by adding varieties of alloying elements and through different heat treatment processes. To produce high-quality, high-tensile steels of uniform quality on a hot strip mill, it is essential to homogenize the steel temperature across the entire strip length at the exit from the final finishing rolling and control the strip cooling temperature precisely thereafter.

After finishing rolling and before coiling, steel strips go through a water cooling table called a run-out table (ROT), which is more than 100 m long. To maintain the quality of the high-tensile steel sheets, it is imperative to control the strip temperature at the end of the ROT, or the coiling temperature (CT), stably within a predefined narrow range. In addition, active control of metallographic structure is essential for producing steel sheets of high mechanical strength, and, for this, it is very important to control the temperature history of the entire coil length minutely during its passage through the ROT. To make this industrially practicable, the technologies described herein have been developed to measure the strip temperature accurately in the water cooling environment of the ROT and control the strip cooling precisely on the ROT using the developed temperature measurement devices.[1–9)]

2. Strip Cooling at Run-out Table of Hot Strip Mill

On a hot strip mill line, steel slabs are heated to approximately 1200°C in reheating furnaces and rolled into thin strips of pre-

* Senior Researcher, Instrumentation & Control Research Lab., Process Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

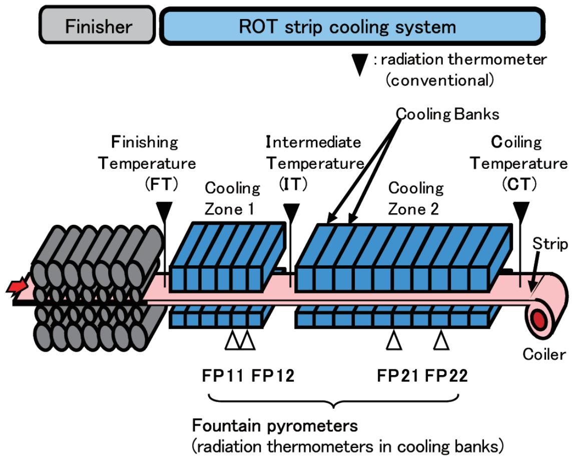


Fig. 1 Run-out table cooling equipment of Kashima Works hot strip mill

scribed thicknesses through roughing and finishing rolling mill stands. At the exit from the final rolling stand, the strip thickness is approximately 1 mm at the thinnest, the temperature is 800–900°C, and the strip is moving at a speed up to 100 km/h. Immediately thereafter, the strips are cooled with water through the ROT, and finally coiled by down coilers; the strips in coil form thus obtained are called hot coils.

The description hereafter details the development activities of the captioned technologies at Kashima Hot Strip Mill Plant.

As seen in **Fig. 1**, the ROT of the hot rolling line is roughly divided into two sections: cooling zones 1 and 2. At the entry to, between, and at the exit from these cooling zones, there are three radiation thermometers to measure the temperature of the strips for metallurgical purposes; the readings of these thermometers are herein referred to as the finishing temperature (FT), intermediate temperature (IT), and CT. For stable temperature measurement, it is necessary to ensure that the strip surface in the thermometer's field of view is completely free of cooling water and vapor, and, to secure the space for this, the devices are provided at a certain distance away from the cooling zones. In contrast, the radiation thermometer of our new development, the fountain pyrometer, is capable of stably measuring the strip temperature in the environment of the cooling zones. Several thermometers are installed under the strip pass line, between the table rollers, and inside each cooling zone. No special measures are taken to remove water and vapor except for water purging, one of the unique features of this new radiation thermometer.

The water supply system of the ROT for strip cooling is divided into sections called cooling banks, and cooling zones 1 and 2 consist of six and ten cooling banks, respectively. Each cooling bank is composed of pipe laminar nozzles above the strip pass line and full-corn type spray nozzles below. There are more than 300 water nozzles in total in the ROT, and the water flow is controlled by on/off switching of water valves of every bank, each of which is responsible for several nozzles and operated under the command of a cooling control model.

3. Strip Temperature Measurement at Run-out Table [1–4]

3.1 Disturbance in strip temperature measurement in cooling zones

The temperature measurement objects, the steel strips, run on table rollers at high speeds with their head ends often violently fluttering vertically. For this reason, to avoid being hit by the strips, radiation thermometers capable of measuring the strip temperature from a distance have long been used.

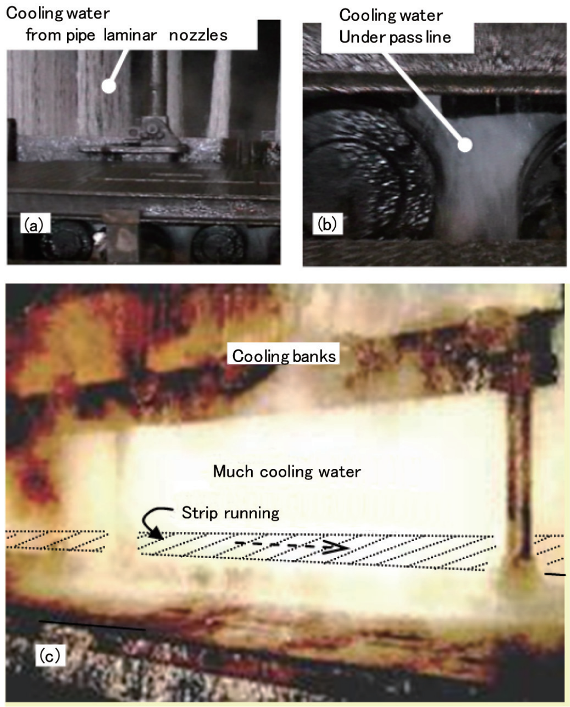


Fig. 2 Measurement condition of cooling banks

Figure 2 shows cooling water in the cooling zones; water constitutes a major disturbance in the temperature measurement. Part (a) shows the cooling water falling from the pipe laminar nozzles. Some of the water stays on the strip after hitting it, and, since it boils, it often turns opaque with vapor bubbles. Part (b) shows the water sprayed from below between the table rollers; there is a large amount of water in small drops under the strip. Part (c) is a view from outside the ROT; drops of water blown up strongly from the lower nozzles fill the space, making it impossible to see the red-hot steel strip. The conditions in the cooling zones change from moment to moment, and the mode of change is different depending on the required degree of cooling, temperature, humidity, and so on. in the plant building. It is essential that the thermometers can function stably and reliably in such tough and diverse environmental conditions and operate almost continuously by requiring as little servicing as possible.

A radiation thermometer determines the temperature of an object by detecting its thermal radiation and using Planck's equation of black body radiation, and so on. When water exists between the thermometer and the object, it absorbs and attenuates the thermal radiation, leading to low readings (absorption error). In addition, when the condition is as seen in parts (b) and (c) of Fig. 2, thermal radiation is scattered by the water drops and the output of the thermometer falls significantly (scattering error). The water drops can be removed from the view range by strong air purging, but this is likely to disturb the cooling condition in the zone, and the reading may not correctly reflect the object temperature (cooling error).

To measure the strip temperature accurately in spite of such violent disturbances, the radiation thermometer for a steel strip in the ROT with fountain water purging has been developed.

3.2 Fountain pyrometers for run-out table

Figure 3 schematically illustrates the structure of the developed thermometer for use in the cooling zones, and **Table 1** its specifications. The unique purging water fountain stabilizes the optical path for radiation detection (control of scattering error), decreases the absorption error by water, and minimizes the influence of the cooling of the strip surface by a purging medium (control of cooling error). To minimize the purging medium's disturbance of the strip cooling condition and unduly cooling the strip surface, a slower flow speed of the medium is preferred, and to remove the disturbing water drops with a slow-flowing medium, the use of water is effective because its density is higher than that of gas. In addition, the use of water is advantageous, as when the vapor and drops of the cooling water are caught in the purging water, they will no longer disturb the measurement.

To decrease the absorption error by water, it is necessary to use the wavelength of light that is least absorbed by water. **Figure 4** shows the spectral transmittance of common city water. Water absorbs light significantly in the wavelength band around 1.0 μm and in another 1.2 μm or more. From this, and to obtain sufficiently good optical detection and minimize the absorption by water, two types of radiation thermometers have been developed: FP1 for thermal radiation 0.83 μm or less in wavelength, which avoids the band of high absorption by water; and FP2 for thermal radiation around 1.1 μm in wavelength. These two types are used for different temperature ranges according to their respective sensitivity bands: FP1 in cooling zone 1, and FP2 in cooling zone 2 (Table 1).

As stated earlier, the cooling water usually exists around the steel strip in the form of small particles. To secure a stable optical path of the thermal radiation in this environment and at the same time avoid unexpected cooling of the steel strip by the purging water, the pyrometers were placed just below the strip pass line such that the purging water does not contact the strip. **Figure 5** shows the result of laboratory evaluation of the scattering error due to the disturbance of the pyrometer by cooling water in the water purging process. The fluctuation of the fountain pyrometer output increases because of the scattering by water drops. However, it was found that by defining the maximum amplitude of the output fluctuation as the scattering error, the fluctuation was within a range of roughly 10°C, which is practically acceptable when $\theta \geq 75°$.[2)]

3.3 On-line temperature measurement in run-out table

The measurement performance of the fountain pyrometer was tested by installing one in a cooling bank, closing the strip cooling water in nearby banks (keeping only the roll cooling water on), and also measuring the strip temperature with another conventional radiation thermometer from above the measuring point of the fountain pyrometer (**Fig. 6**). Strips about 1 mm in thickness were used for the test because the temperature difference in the thickness direction was negligible. The graph in Fig. 6 is the result of a specimen strip; here, the reading of the upper surface temperature fell locally at some points to levels significantly lower than that of the fountain pyrometer measuring from below. This was due to water getting in the range of view of the upper radiation thermometer.

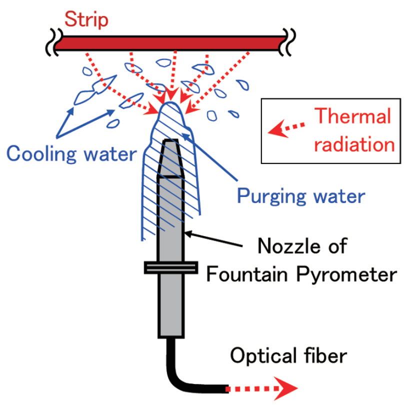


Fig. 3 Fountain pyrometer (radiation thermometer in cooling bank)

Table 1 Specifications of fountain pyrometer

Type	FP1	FP2
Wavelength	–0.83 μm	1.1 μm
Temperature range	500–1 200 °C	360–800 °C
Responsiveness	10 ms	20 ms
Position	Cooling zone 1	Cooling zone 2
Notation	FP11, FP12	FP21, FP22

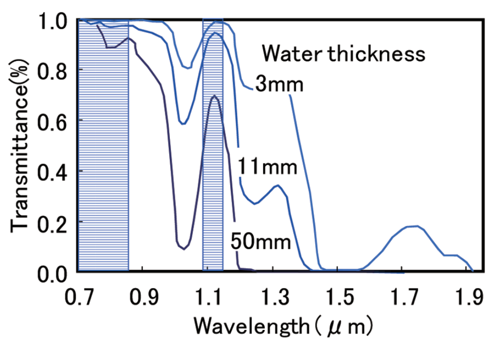


Fig. 4 Spectral transmittance of city water

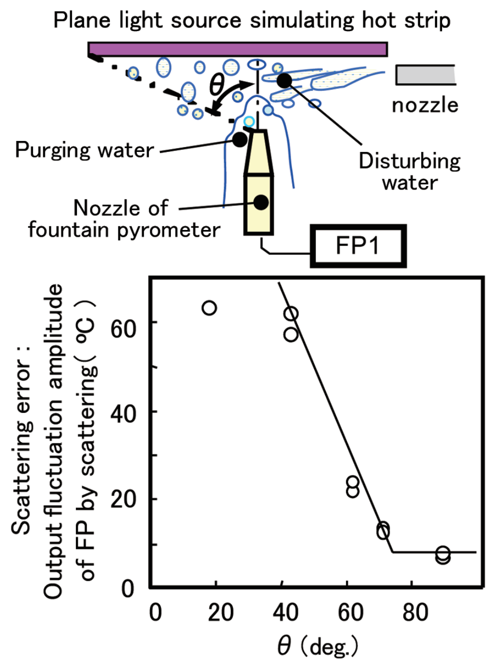


Fig. 5 Scattering error versus θ

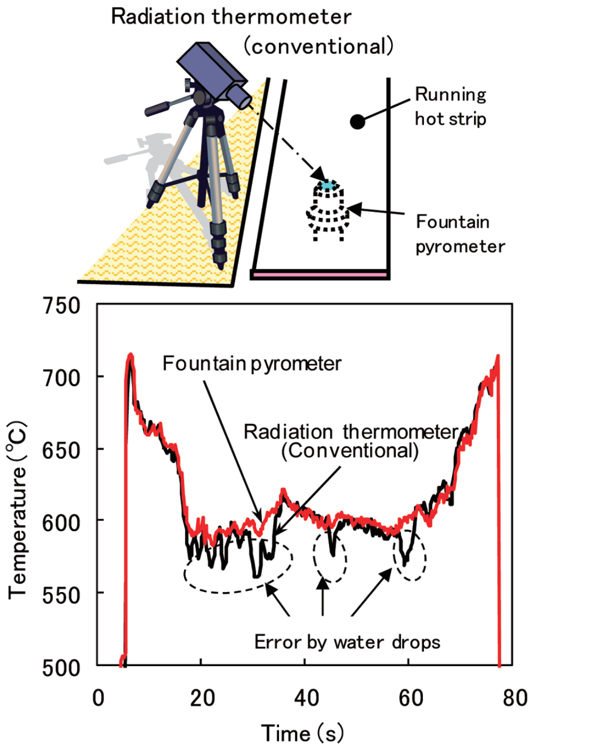


Fig. 6 Comparison of readings by developed fountain pyrometer and conventional radiation thermometer

In contrast, there were no such temporary falls in the reading of the fountain pyrometer from under the strip. Note that, comparing the readings between the upper thermometer and fountain pyrometer excluding the local falls of the upper thermometer, the readings of the two agreed well with each other; the mean deviation was 2.0°C, and σ=2.8°C. The authors separately confirmed that the measurement accuracy of the fountain pyrometer was also high when the strip cooling water was on at the bank where it was installed.[2)]

4. Cooling Control in Run-out Table with Fountain Pyrometers

Steel strips are cooled at the ROT principally under what is known as CT control, wherein steel sheets of prescribed mechanical properties are obtained by controlling so that the strip temperature at the time of coiling (CT) is as close to a target as possible. In the CT control, several control points are supposed in each strip at certain intervals along the entire length, the temperature at every control point at the time of coiling is predicted using a temperature calculation model (**Fig. 7**), and the cooling system of the ROT is set and operated such that the predicted temperature of every control point aims for the target CT. Here, the control points are tracked, and the cooling at each of them is controlled in consideration of the temperature before cooling (FT) and the change in the strip travelling speed from time to time. Every valve of each cooling bank is opened and closed in cycles which are often shorter than a second. This cooling control is called dynamic control since it regulates the strip cooling system of the ROT continuously.[10)]

4.1 Feed forward control with fountain pyrometers (FP-FF Control)[5, 6)]

In commercial operation of hot strip mills, the real strip temperature often deviates from the calculated temperature because of disturbances. When the deviation is significant, it is impossible to exactly achieve the target CT, even with dynamic control. Thus, as a corrective measure, feedback control has been practiced to minimize the deviation of the CT. This, however, does not always work effectively for the strip head end, which run at changing speeds. In addition, because of the delay in the response of the water valves, the long distance from the temperature measurement points to the cooling banks, and the consequent long dead time, satisfactory control effects are not always obtained.

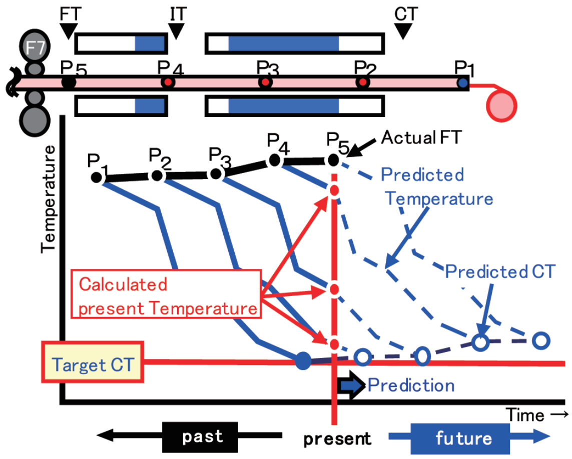


Fig. 7 Prediction of coiling temperature at control points

Furthermore, when the strip temperature falls below a certain point during cooling, the boiling behavior of water on the strip surface changes, the strip temperature falls rapidly (this temperature range is called the transition boiling range), and it becomes difficult to accurately control the CT. Because the CT of high-tensile steel is lower than that of ordinary carbon steel, the temperature easily falls to outside the target range owing to the change in the water boiling behavior, and improvement of the CT control has been an important challenge. In view of this, the authors tackled the task of developing the technology of feedforward control based on strip temperature measurement at some positions in the cooling zones using the fountain pyrometers (FP-FF control).

The concept of the FP-FF control consists of measuring the strip temperature real time during cooling at two points in cooling zone 2 using FP21 and 22 and, based on the temperature readings, applying feedforward control in a multi-staged manner. **Figure 8** shows how the FP-FF control is applied to a control point of a strip; when a control point reaches the position of FP21, the actual temperature reading is compared with the calculated temperature reading, and the valve settings of the downstream cooling banks are revised according to the difference between the reading and calculated temperature. The same procedure is conducted based on the measurement by FP22 provided at a position further downstream. These control procedures are conducted regarding every control point of a strip to enhance the accuracy of the CT control.

As an example of the application of the FP-FF control, **Fig. 9** shows the temperature change of a coil at different positions (IT, FP21, and CT) and that of the water flow of the cooling banks from FP21 to the measuring point of CT. In this particular case, where the target CT was 450°C, an unexpected temperature disturbance occurred at cooling zone 2 after the measurement of IT, and a sudden over cooling by roughly 30°C was detected by PF21. To cope with this situation, the water flow at the banks downstream of FP21 was

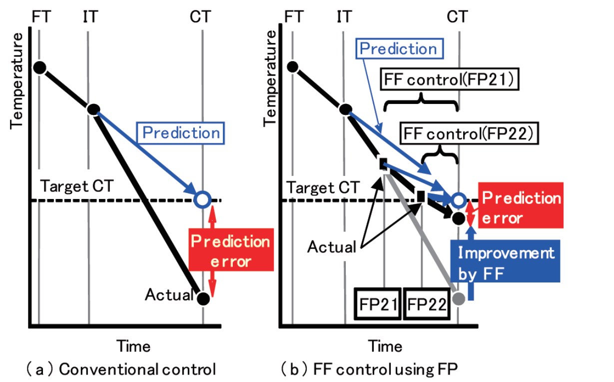


Fig. 8 CT control without and with fountain pyrometers (FP-FF control)

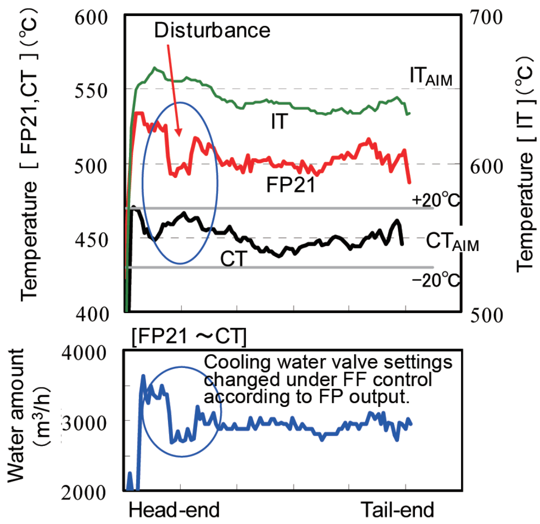


Fig. 9 Example of the new coiling temperature control using FP (FP-FF control)

decreased by about 600 m^3/h in a feedforward manner to minimize the deviation of CT. As a result, the CT actually measured was confined within the range of the target CT (CT_{AIM}) ±20°C in the whole coil length.

The FP-FF control is applied mainly to high-tensile steels and low-CT steels. **Table 2** summarizes the result of mass evaluation of the FP-FF control effects. The evaluation index was the length of the strip portions where the CT was within a range of CTAIM ±20°C divided by the total length of the strips rolled during the evaluation period. Thanks to the FP-FF control, the ±20°C hitting ratio of high-tensile steel strips was improved by 5.8% in the case of 440 MPa steels, by 9.7% in the case of 550 MPa steels, and by 6.4% in the average of all low-coiling-temperature steels.[5, 6]

As has been stated above, the feedforward strip cooling control using the strip temperature measurement in the ROT by the fountain pyrometers has brought about an improvement in strip cooling control based on the actual strip temperature during cooling and higher control accuracy of the CT.

4.2 Cooling pattern control[7–9]

Figure 10 illustrates the concept of strip cooling pattern control. To manufacture a steel strip of improved mechanical properties, it is necessary to purposefully control its metallographic structure. According to the example in Fig. 10, a strip is at first rapidly cooled after rolling, then the rapid cooling is stopped when the strip temperature falls to the zone of ferrite formation, and finally, after securing enough time in the zone, the strip is rapidly cooled again to the prescribed CT. The metallographic structure of the hot-rolled strips is changed as desired through the cooling pattern control as above, and, by so doing, it is possible to minimize the fluctuation of the strength of high-tensile products and improve their workability and other mechanical properties. To maintain a cooling pattern uniformly in the whole length of a strip running at changing speeds, it is necessary to follow minutely the temperature history of every control point. This means that in addition to the aforementioned FP-FF control, it is necessary to simultaneously control the end-point temperature of the rapid cooling immediately after finishing rolling and the time of the subsequent slow cooling to prescribed values.

Table 2 Improvement of coiling temperature by FP-FF control

Hot coils		Percentage improvement of strip length within ± 20 °C
High tensile steel	440 MPa	5.8 %
	590 MPa	9.7 %
Low temperature coiling steel		6.4 %

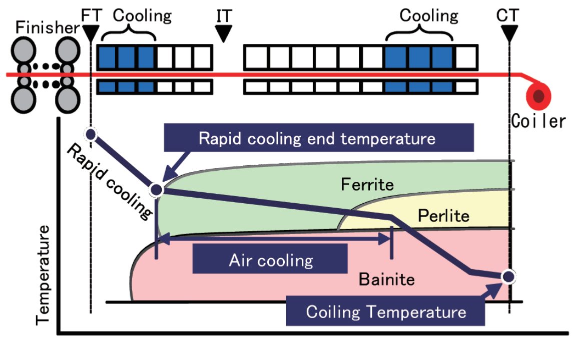


Fig. 10 Schematic diagram of cooling pattern control

Using the dynamic control of the strip cooling on the ROT, the temperature curve of every control point is predicted rapidly in short calculation cycles. In case of the cooling pattern control, as the end-point temperature of rapid cooling, the time of intermediate air cooling and the CT fall within their target range based on the calculation of the dynamic control, each value of cooling banks is regulated. The cooling pattern is, however, a product of the temperature calculation model and always contains certain errors, which inevitably affect control accuracy. As a corrective measure, the developed fountain pyrometers, provided in the cooling zones (FP11, FP12, FP21, and FP22), are used effectively for improving the accuracy of the cooling pattern control. As seen in **Fig. 11**, to improve the accuracy of the strip cooling control at the ROT, two functions of the cooling pattern control, namely those on the end-point temperature of the rapid cooling and the CT, have been added to the dynamic cooling control.

Figure 12 compares the effects of the feedforward control of CT and the cooling pattern control on a commercial hot strip mill. The graphs show the actually measured temperature and calculated cooling curves of the control points (P1, P2, P3 …) along the length of a strip during the travel from the final rolling stand to the coiler. Here, the vertical axis shows the difference of temperature drop from the

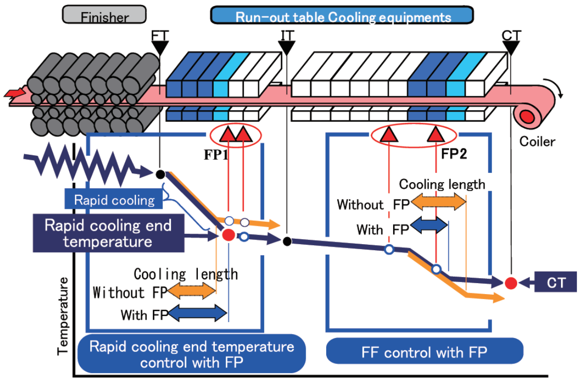
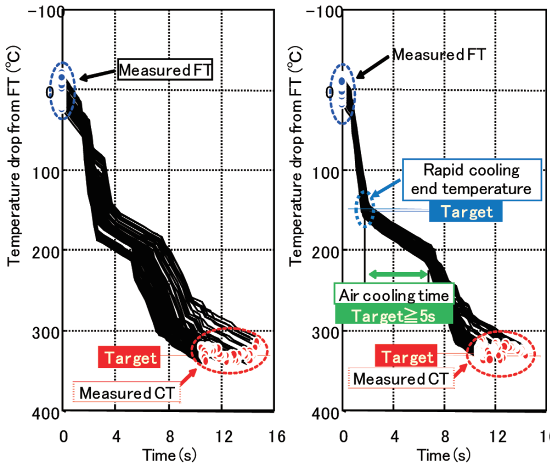


Fig. 11 Cooling pattern control using fountain pyrometers



(a) Coiling Temperature Control (b) Cooling Pattern Control

Fig. 12 Coiling temperature control and cooling pattern control using fountain pyrometers

target value of FT, and the calculated temperature change thereafter at each of the control points is plotted. Whereas under the CT control alone (part (a)), the cooling patterns of the control points are widely different (for example, the time for a temperature fall by 200°C is varied), with the cooling pattern control (part (b)), in spite of strip speed changes during rolling, the fluctuation of the temperature history to the end-point temperature of the rapid cooling and that of the intermediate air cooling time are smaller, and the CT is closer to the target in the entire coil length. Cooling pattern control has been proved capable of improving the mechanical properties of high-tensile steel sheets.[8, 9)]

5. Conclusion

This paper has presented the technology required to stably and accurately measure steel strip temperature in the tough and quickly changing environment of cooling zones in the ROT of a hot strip mill, and also the development of thermometers called fountain pyrometers which can control the strip cooling on an ROT. These technologies have made it possible to accurately control the strip temperature across a wide temperature range, including the transition boiling range, which was difficult to achieve by conventional cooling control methods. As a result, it became possible to improve the hitting ratio of the CT of high-tensile steel strips and produce this type of product more stably. It became possible, in addition, to follow and control the strip temperature history acculately during the travel through the ROT, and, consequently, stably produce sheet products of excellent mechanical properties that require precision control of their metallographic structure. These technologies were developed at Kashima Works and are being expanded to the hot strip mills of the other works of the company.

References

1) Honda, T. et al.: ICCAS-SICE2009 Proceedings. 2009, p. 2774
2) Honda, T. et al.: Tetsu-to-Hagané. 96 (10), 592 (2010)
3) Uematsu, C. et al.: CAMP-ISIJ. 22, 1054 (2009)
4) Honda, T. et al.: ISIJ International. 53 (5), 841 (2012)
5) Nakagawa, S. et al.: ICCAS-SICE2009 Proceedings. 2009, p. 2778
6) Nakagawa, S. et al.: Trans. Soc. Instrument and Control Engineers. 46 (8), 463 (2010)
7) Tachibana, H. et al.: CAMP-ISIJ. 23, 1054 (2010)
8) Tachibana, H. et al.: Proc. 2011 Japanese Spring Conference Tech. Plasticity. 2011, p. 119
9) Tachibana, H. et al.: CAMP-ISIJ. 25, 1026 (2012)
10) Takahashi, R.: Control Technology in Steel Industry. Published by Corona Publishing Co. Ltd., Tokyo, Japan, 2002

Tatsuro HONDA
Senior Researcher
Instrumentation & Control Research Lab.
Process Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Shigemasa NAKAGAWA
General Manager, Head of Dept., Dr. Eng
System & Control Engineering Dept.
Equipment Div.
Oita Works

Hisayoshi TACHIBANA
Senior Manager
Plant Control Development Dept.
Plant Engineering & Maintenance Div.
Kashima Works

Chihiro UEMATSU
Senior Manager
Instrumentation & Inspection Unit
Nippon Steel & Sumikin Technology Co., Ltd.

Yasuhiko BUEI
Senior Manager
Sheet & Coil Planning Dept.
Sheet & Coil Div.
Kashima Works

Koichi SAKAGAMI
Senior Manager, Head of Dept.
Sheet & Coil Planning Dept.
Sheet & Coil Div.
Kashima Works