International Journal of Hybrid Information Technology
Vol. 9, No.10 (2016), pp. 11-20
http://dx.doi.org/10.14257/ijhit.2016.9.10.02

# Thermal Behavior of Hot Strip in Finishing Mill of Hot Rolling Process

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## Abstract

*To apply efficient rolling conditions in the finishing rolling process, a correct prediction of the behavior of the strip temperature is required. This study is focused on the temperature distribution of the strip temperature from FET to FDT of the actual finishing rolling process. The heat transfer phenomena generated during the finishing rolling process, such as heat generation, cooling and conducting, were modeled in this study using the finite difference method. Using various heat transfer phenomena generated in the finishing rolling process and the correlation formula of spray cooling coefficient, the calculation accuracy was improved and a simulator to predict the temperature distribution of strip was prepared. The calculated result is compared to the online model used in the actual industry.*

***Keywords****: Hot strip, Finishing mill, Water jet spray, Spray cooling coefficient, Bisection method, Correlation equation*

## 1. Introduction

Unstable temperature distribution and incorrect temperature prediction of strip in the hot finishing rolling process places a big burden on the facility in various forms, including deterioration of material quality. For this reason, the strip temperature must be correctly predicted during the finishing rolling process.

Lee *et al*. [1] verified the reliability of the heat transfer phenomena, such as deformation heating, frictional heating and contact heat transfer generated in the finishing rolling process. As a result, the simulator was prepared to predict the heat transfer phenomena, spray cooling convection cooling and conduction inside the strip generated in the finishing rolling process. Choi *et al*. [2] reported correct temperature prediction due to the significant temperature change in the scale removal area during the finishing rolling process related to the spray. A study on cooling efficiency in which cooling effect by high pressure water jet spray was changed according to the spray setting in respect of spray pressure and height was performed. Goldstein *et al*. [3] presented the convection heat transfer on the plate surface in association with Naphthalene sublimation and various correlation formula. Hawbolt *et al*. [4] performed a study on heat transfer coefficient and pressure between the strip and the work roll, and strip temperature according to lubrication and rolling condition during the rolling process.

ISSN: 1738-9968 IJHIT

Kim *et al*. [5] presented a model to predict the temperature distribution inside the strip in the direction of its thickness during the finishing rolling process. This model can be selected as the standard for deformation heating, frictional heating and contact heat transfer at the bottom of the stand. Kim [6] performed a study on the model to predict the strip temperature during the finishing rolling process by considering deformation heating, frictional heating and contact heat transfer generated in the rolling process and deriving the spray cooling coefficient correlation formula.

This study will develop a temperature prediction model depending on the changes in the thickness and temperature of the material during the hot finishing rolling process. A more accurate material temperature will be predicted by deriving the spray cooling correlation formula of a spray cooling device. The spray cooling correlation formula for each spray cooling device in the finishing rolling process will be used to derive the correlation formula about surface temperature and water filling amount of the material by using the operation data.

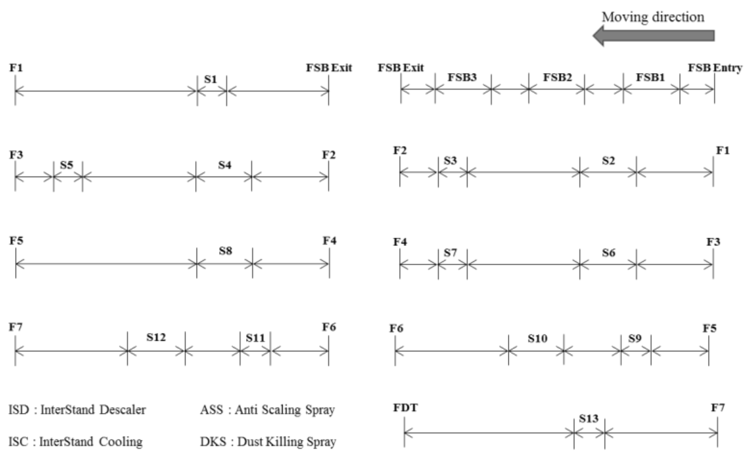


**Figure 1. Layout of Finishing Mill Process**

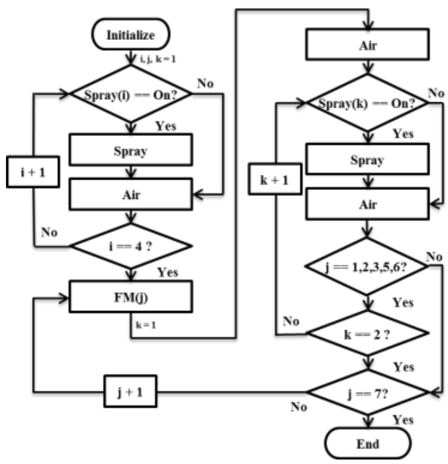


**Figure 2. Flow Chart for Simulation**

## 2. Analysis Model

Figure 1 shows the entire layout of the finishing rolling process. Finishing rolling process is performed along with heating (deformation heating and frictional heating) and cooling (contact transfer) at each position of 7 stands (F1 – F7) as shown in Figure 1 After that, the strip is cooled by 16 water jet sprays (FSB1 – FSB3, S1 – S13), along with scale removal and lubrication action.

## 3. Differential Equation Analysis and Boundary Conditions

< Governing equation>

Based on the 2D heat conduction governing equation (1), the internal temperature distribution inside the strip was calculated by applying Forward-Time Central-Space (FTCS) of the finite difference method.

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \dot{q}(x,y) \quad (1)$$

$$k\frac{\partial T}{\partial x}\left(\pm\frac{H}{2}\right) = h_{side}\left[T\left(\pm\frac{H}{2}\right) - T_{sur}\right] + \epsilon\sigma\left[T^4\left(\pm\frac{H}{2}\right) - T_{sur}^4\right] \quad (2)$$

In free area, conduction, convection cooling, radiation cooling and spray cooling are applied. Convection cooling and radiation cooling are calculated using Equation (2), and spray cooling is calculated in association with water filling area and amount, spray cooling coefficient of spray and water temperature.

In rolling area, the heat transfer generations, such as conduction, deformation heating, frictional heating and contact heat conduction are included in $\dot{q}(x)$ at Equation (1).

< Flowchart of simulation >

Figure 2 shows the entire flow chart of the numerical temperature prediction simulation. The temperature is calculated according to On/Off condition of FSB and Spray 1 after initial-setting. Next, the calculation is performed according to each condition by distinguishing the areas with two sprays and one spray, simultaneously considering the rolling from FM1 to FDT and the On/Off condition of the spray.

## 4. Results and Discussion

### 4.1. Spray Flow Pattern

Depending on the processing conditions of the material, various water jet spray patterns are used. The influence of the spray pattern was observed by using the water filling conditions, as shown in Table 1.

**Table 1. Water Jet Spray Flow Rate of Case1 and Case2**

| | FSB1 | FSB2 | FSB3 | Spray2 | Spray4 | Spray6 | Spray8 | Spray9 | Spray11 |
|---|---|---|---|---|---|---|---|---|---|
| Case1 | 100% | 100% | 100% | 100% | 40% | 0% | 0% | 0% | 0% |
| Case2 | 100% | 100% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

The calculation results for each water filling case are as shown in Figure 3 and Figure 4 They show the temperature distributions on the surface (Top and Bottom) and the center part of the strip during the cooling period. The temperature rise on the center part is usually caused by deformation heating in the inside, and we can see the temperature rise at 7 rolling areas. The temperatures at the top and bottom are sharply changed by the spray cooling.

 

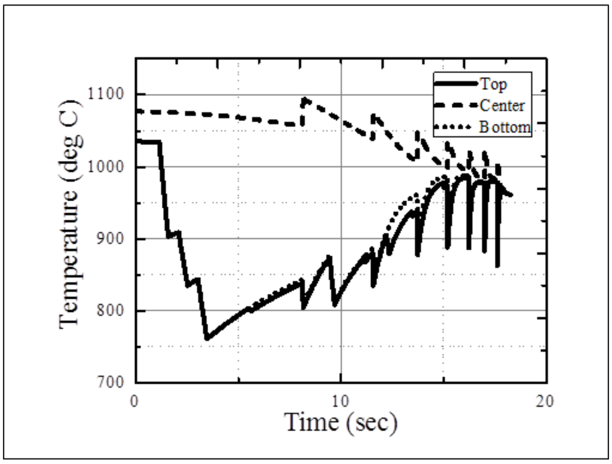


**Figure 3.a. Flow Chart for Simulation**

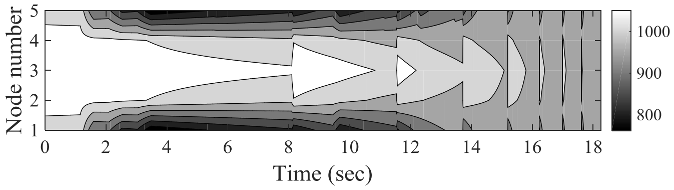


**Figure 3.b. Low Chart for Simulation**

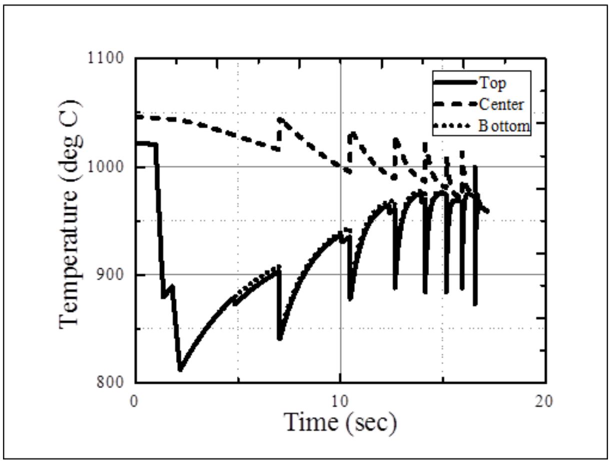


**Figure 4.a. Flow Chart for Simulation**

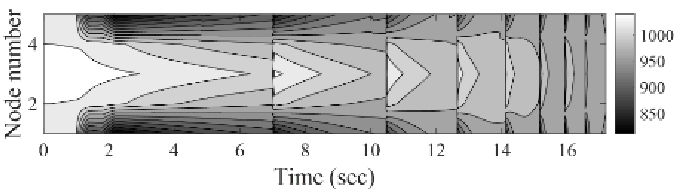


**Figure 4.b. Flow Chart for Simulation**

**Table 2. Water Jet Spray Pattern of Simulation Model**

| Spray | FSB1 | FSB2 | FSB3 | Spray1 | Spray2 | Spray3 | Spray4 | Spray5 |
|---|---|---|---|---|---|---|---|---|
| Flow rate | 100% | 100% | 100% | 100% | 100% | 100% | 70% | 100% |
| Spray | Spray6 | Spray7 | Spray8 | Spray9 | Spray10 | Spray11 | Spray12 | Spray13 |
| Flow rate | 60% | 100% | 50% | 100% | 40% | 100% | 30% | 100% |

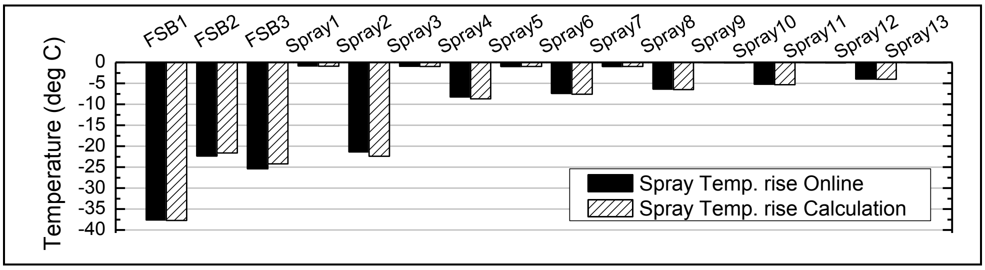


**Figure 5. Amount of Temperature Change on Each Spraies**

In Figure 3 a, three dramatic temperature changes (129℃, -73℃, -82℃) at the top and bottom in the time prior to the first rolling area are due to the cooling by FSB 1, 2, 3. After the first rolling, the biggest cooling (-64℃) of the surface is due to the cooling by Spray 2. As except for FSB and Spray 2, the spray only affects the top of the strip, the temperature shows the difference between top and bottom in the spray area just next to the second rolling area. Since the spray does not work after the third rolling area the temperature difference is gradually reduced.

In Case 2, the spray is turned off after FSB2. Therefore, as shown in Figure 4 a, a significant amount of cooling is only generated by FSB1 and FSB2. A small amount of cooling is generated several times by Sprays 1, 3, 5 and 7 at the temperature of the Top position during the finishing rolling process. In the area other than the rolling area and the water filling area, temperature is changed by convection, radiation cooling and conduction inside the strip.

In Figure 3 b and Figure 4 b, internal temperature distribution and change of the strip are displayed as contour during the calculation process. In the initial temperature distribution, the surface temperature (Node 1 and 5) is being dramatically cooled by the spray and the inside temperature is being cooled as the center temperature is conducted into the surface. In the rolling area, the center temperature is dramatically raised by the deformation heating. Spray 4 is placed in the section between 12 sec – 14 sec in Figure 3 b Since Spray 4 only affects the top surface, the temperature of the lower part based on the center part (Node 3) is higher than that of the upper part.

### 4.2. Amount of Water Jet Spray

The strip temperature varies dominantly by the cooling of the spray. The cooling amount($Q_{spy}$) is calculated in association with spray cooling coefficient, cooling efficiency, spray area and the surface temperature of the strip. Figure 5 shows the compared results of online model and the calculated results under the water filling condition of Table 2. As among the sprays, FSB1 fills the greatest water amount, the cooling amount is about -37.6℃, which is the largest amount. Since FSB2 & 3 and S2 have the same spray cooling coefficient, they represent similar temperature differences. When sprays 4, 6, 8, 10 and 12 have the same water filling amount, their spray cooling coefficients are equal, but they have different water filling rates and different strip surface temperatures as shown in Table 2. Therefore, their cooling amounts are about -8.5℃, -7.5℃, -6.5℃, -5.3℃ and -4.0℃, respectively. When sprays 1, 3, 5 and 7 have the same water filling amount, their spray cooling coefficients are equal. As their water filling amounts are low, their cooling amount is also low.

Figure 6 compares the measured result to that of calculation of the model used in this study. (numerical analysis method, cooling condition and heating structure). The error rate between the calculated FDT (Finishing Delivery Temperature) and measure FDT is calculated using Equation (3).

The calculated data show two error distributions of -6.5 % - 0 % and 0.5 % - 8 %. This study could obtain the improved normal distribution as shown in Figure 7, when it is calculated by using the learning factor. The learning factor is the compensation factor used to reduce the temperature error for the next calculation through the feedback of the error previously calculated.

$$\text{Error rate}(\%) = \frac{\text{Measured FDT} - \text{Calculated FDT}}{\text{Measured FDT}} \times 100 \qquad (3)\backslash$$

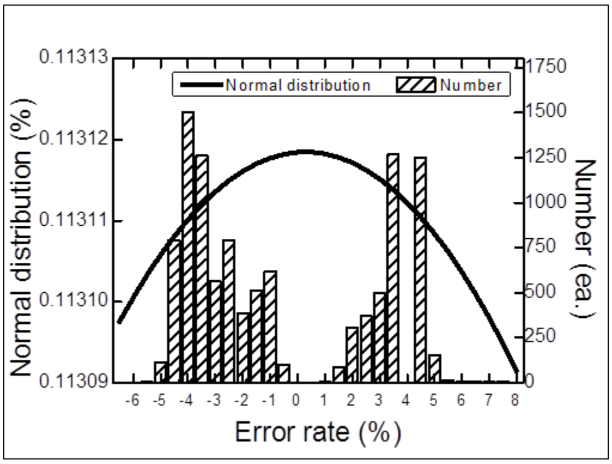


**Figure 6. Normal Distribution on Error Factor Ratio of Calculated FDT and Measured FDT**

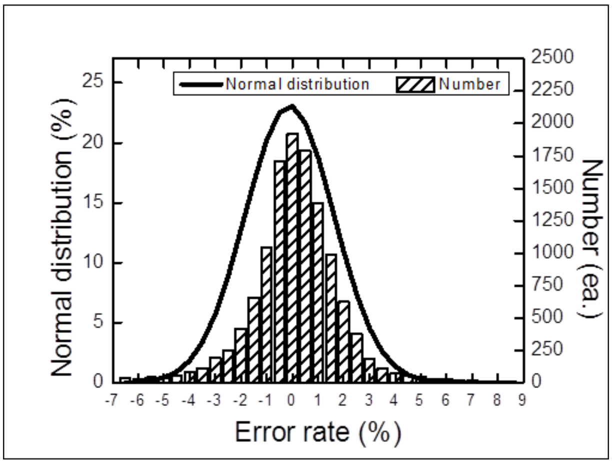


**Figure 7. Normal Distribution on Error Factor Ratio of Measured FDT and Calculated FDT by Learning Factor**

 

This means that the parameters generating error in the calculation must be modified in order to predict the correct strip temperature. In short, the applied spray cooling coefficient must be modified.

Figure 8 shows the spray cooling coefficient and the correlation equation of FSB1 and FSB3. For the spray coefficient, the bisection method of the numerical analysis method was used. For the correlation equation about the spray coefficient, the exponential equation with the biggest $R^2$ was used. This study used 12,000 coil data to predict the spray cooling coefficient applied in the field. The correlation equation indicates the correlation formula of the spray correlation coefficient for the corresponding spray. Using this equation, we can correctly predict the spray cooling coefficient for the surface temperature of strip and the water filling amount of spray.

The equations for the derived spray cooling coefficient are listed from Equation (4) to Equation (10).

$$\text{FSB1} \rightarrow y = 717.94e^{0.0025x} \quad (4)$$

$$\text{FSB2} \rightarrow y = 5683.4e^{-0.0001x} \quad (5)$$

$$\text{FSB2} \rightarrow y = 2.5 \times 5683.4e^{-0.0001x} \text{(In the case where reciprocal action was not applied.)} \quad (6)$$

$$\text{FSB3} \rightarrow y = 243487e^{-0.008x} \quad (7)$$

$$\text{FSB3} \rightarrow y = 10 \times 243487e^{-0.008x} \text{(In the case where reciprocal action was not applied.)} \quad (8)$$

$$\text{ISD} \rightarrow y = 336309e^{-0.006x} \quad (9)$$

$$\text{ISC} \rightarrow y = 3.0809w^{-1}e^{0.0076x} \quad (10)$$

The variables in the spray cooling coefficient correlation formula are as follows : [x=Inlet surface temperature of each spray (℃),y=Spray cooling coefficient of each spray $h_{water}$ ($W/m^2 \cdot K$),w=Spray flow(%)]

The verification of the calculated result was confirmed by applying the derived spray cooling coefficient correlation formula. The result was verified with random data from 12,000 coil data unused in the derivation of the spray cooling coefficient. Figure 9 shows the result FDT error rate and its normal distribution. The average error rate was 2.45%, and the tolerance was ±3%. Also strong concentration is showing thanks to 83% of data within the error range of ±3% from the average error rate among the 12,000 pieces of data. Standard deviation of 0.0248 also shows high concentration of data in terms of numbers.

With this result we can check the improvement of the FDT calculation by applying the spray cooling coefficient correlation formula.

## 5. Conclusion

In this study, the two dimensional numerical simulation has been performed to determine the transient temperature distribution of the strip. At first, the deformation heating, processing heating, contact heat transfer, frictional heating, cooling by water jet, radiation and convection cooling was analysed in the finishing rolling process. Based on this result, a thermal modeling was presented to predict the temperature behavior of strip in a finishing rolling process.

In addition, this study derived the correlation formula for the spray cooling coefficient about the spray inlet surface temperature and water filling amount. The accuracy of the FDT calculation result was confirmed by using this correlation equation.

A program was also developed to predict the temperature distribution. The program developed in this study can be used to set proper rolling conditions at the industry by applying initial and rolling conditions.

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