Effective Work Roll Cooling toward Stand Reduction in Hot Strip Process

Temsiri Sapsaman, Anocha Bhocarattanahkul

***Abstract*—**The maintenance of work rolls in hot strip processing has been lengthy and difficult tasks for hot strip manufacturer because heavy work rolls have to be taken out of the production line, which could take hours. One way to increase the time between maintenance is to improve the effectiveness of the work roll cooling system such that the wear and tear more slowly occurs, while the operation cost is kept low. Therefore, this study aims to improve the work roll cooling system by providing the manufacturer the relationship between the work-roll temperature reduced by cooling and the water flow that can help manufacturer determining the more effective water flow of the cooling system. The relationship is found using simulation with a systematic process adjustment so that the satisfying quality of product is achieved. Results suggest that the manufacturer could reduce the water flow by 9% with roughly the same performance. With the same process adjustment, the feasibility of finishing-mill-stand reduction is also investigated. Results suggest its possibility.

***Keywords*—**Work-roll cooling system, hot strip process adjustment, feasibility study.

I. Introduction

TODAY, 85% of hot rolled coils produced in Thailand annually are delivered to local customers in the form of finished products for use in automobiles, steel structures, steel pipes, home appliances, and a variety of other products. Currently, hot rolling mill process is designed to maintain competitive position through reduced operating costs, broadened product line, improved product quality, and increased production capacity. To increase the competitive edge the manufacturer wants to increase the time between maintenance, which is a lengthy and difficult process. An effective work roll cooling system can slow down the chance of wear and tear and keep the operation cost low.

II. Literature Reviews

Studies on hot strip process involve solving heat transfer equations that lead to process simulation. The geometry of water sprays on work-roll cooling system in hot strip mill has recently been involved with simulation and optimization. However, to our knowledge a quick reference for the effective cooling that helps manufacturer adjust the water flow of the work roll cooling is not yet available.

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A. Solution of Heat Transfer Equations

Pawelski [1] developed an analytical solution for the heat transfer equation between work roll and strip (roll-bite region) to find the heat transfer coefficient in this region. This coefficient is a function of roll speed, scale thickness, physical properties of roll and strip, and roll-bite contact time. Van Steden and Tellman [2] considered more detailed calculations that solved the heat transfer equation in two steps. They found the actual heat transfer coefficient for spraying based on the experimental data and applied it for numerical simulations. Cooling heat transfer coefficient was a function of water pressure, distance from nozzle to work roll, water flow per unit area created on work roll, and spray angle.

Ginzburg et al. [3] used experimental results from Van Steden and Tellman [2] and considered work roll temperature effect, which causes water evaporation, on heat transfer coefficient. Based on this assumption, they developed a model called Coolflex based on finite difference method in radial and axial directions. Ginzburg et al. [4] also proposed a new roll thermal crown cooling system to obtain the best cooling conditions. Saboonchi and Abbaspour [5] used the result of cooling heat transfer coefficients from Ginzburg et al. [3] and considered a detailed radiation and roll bite heat transfer calculation to develop a new simulation model.

Based on finite-difference method [5], [6], a computer program was developed to solve the work roll heat transfer equations in the unsteady state with varying boundary conditions. Besides, a computer model was developed under transient condition to calculate the temperature and thermal crown profile in the work roll. Results showed that the mean surface temperature increased during the rolling and decreased during the cooling for each strip. The core temperature gradually increased as rolling program continued. Therefore, cooling system affected the surface more than the core. In [5], the effect of geometric parameters of water spray on work roll temperature was explained.

B. Work Roll Cooling

Lin [7] presented a detailed theoretical analysis of selecting the maximum and minimum spray deposition rates under steady-state conditions during the spray-rolling process. Predictions were made on the basis of the preceding theoretical analysis. The minimum spray deposition rate was controlled by the removal of porosity, and by the removal of prior droplet boundaries with an increased initial liquid fraction at the deposit interfaces. The maximum spray deposition rate was controlled by the drag-in angle, and by the distance between the nozzle and the deposited material's

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:8, No:7, 2014

surface with an increase in roll diameter or a decrease in distance between the nozzle and the roll-axis plane. Both calculated maximum and minimum spray deposition rates markedly increased with an increase in the roll diameter and roll rotational frequency. Moreover, the calculated minimum spray deposition rate increased slowly with a decrease in the initial liquid fraction at the deposit interface.

Schroeder [8] investigated and simulated temperature on and below the work roll surface during rolling, taking common experience into consideration. Roll surface temperature in contact with strip was found similar at all stands and varies around 600 to 700°C depending on the rolling conditions. Also, low heat conductivity of work roll material or early cooling reduced the area of temperature variations. Work-roll surface temperature was a function of nozzle distance from the work roll, nozzle angle with work roll surface, water flow per unit area created on work roll, water pressure in the nozzle, and work roll surface temperature.

C. Hot Strip Process Simulation

This work uses Hot Strip Mill Model (HSMM), an off-line, stand-alone microstructure evolution simulation tool, to study the relationship between the work roll temperature reduced by cooling and the water flow. This program is used because the quality of finished product can be monitored and all simulations are run with satisfied product quality. In HSMM the austenite grain growth kinetics is described by statistical grain growth model [9], and the Shercliff-Ashby [10] model is used to predict the contribution of microalloying elements to the final mechanical properties. The structure-property relationships are described with equations developed by Choquet et al. [11], and AlN precipitation in the DQSK steel is predicted by incorporation with the precipitation model proposed by Duit et al. [12].

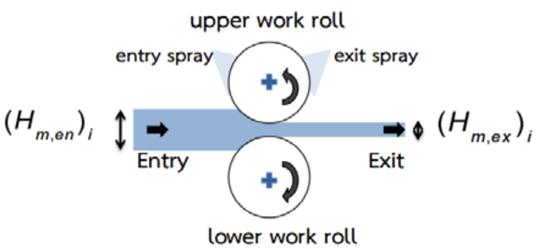

Fig. 1 Finishing-mill station and work roll cooling system

III. Simulation

The HSMM simulates the entire hot rolling process but the main focus is on the finishing mill, which consists of rolling stations shown in Fig. 1. The strip is pressed through upper and lower work rolls with the pulling force from rolling action. The work roll cooling system is generally located on both entry and exit sides. Simulations produce satisfying quality of product by adjusting the strip exit thickness at each station of the finishing mill, where $(H_{\mathrm{m,en}})_i$ is the strip entry thickness at m^{th} station, m=1,2,…,M and M = 4,5,6,7; $(H_{\mathrm{m,ex}})_i$ is the strip exit thickness at m^{th} station, m=1,2,…,M and M = 4,5,6,7. Hence,

$$(H_{\mathrm{m,ex}})_i = (H_{\mathrm{m+1,en}})_i.$$

Subscript i indicates the benchmarked simulation, and subscript f indicates the comparing simulation.

All simulation runs set the work-roll diameter of 800mm, work roll material as high chromium, and the rolling speed of 5 mm/s. The benchmarked simulation has strip exit thickness at the last station, $(H_{\mathrm{M,ex}})_i$, of 3mm, hot rolling coil thickness of 2.96mm, and the number of finishing-mill station of 6 (M=6). The comparing simulation runs set parameters for two different purposes. First is to obtain the relationship between the work roll temperature reduced by cooling and the water flow to use as a quick reference for effective cooling, and second is to investigate the possibility of reducing the number of finishing-mill stations. For the first purpose the number of stations stays at 6, but $(H_{\mathrm{M,ex}})_i$ is reduced to 2.5 mm; then the water flow of work roll cooling is changed to see its effects on the work roll reduced temperature. For the second purpose the number of stations is reduced to 5 and 4, but $(H_{\mathrm{M,ex}})_i$ stays at 3mm; then the water flow of work roll cooling is changed.

In all comparing simulation runs, exit thickness at the n^{th} station needs adjustment [13] so that the satisfying quality of product is achieved, where n = 2, 3,…M-1. The exit thickness of the n^{th} station, $(H_{\mathrm{n,ex}})_f$, becomes

$$(H_{\mathrm{n,ex}})_f = (H_{n,\mathrm{en}})_f - \Delta H_{n,r} - \Delta H_{n,i} \tag{1}$$

$$\Delta H_{n,r} = \frac{\Delta H_{n,i}}{\sum_{n=2}^{M-1} \Delta H_{n,i}} \Delta H \tag{2}$$

$$\Delta H_{n,i} = (H_{\mathrm{n,en}})_i - (H_{\mathrm{n,ex}})_i \tag{3}$$

For the case of reducing $(H_{\mathrm{M,ex}})_i$, ΔH is defined as

$$\Delta H = (H_{\mathrm{M,ex}})_i - (H_{\mathrm{M,ex}})_f \tag{4}$$

For the case of reducing the number of stations to N, ΔH is defined as

$$\Delta H = (H_{\mathrm{N,ex}})_i - (H_{\mathrm{M,ex}})_i \tag{5}$$

For last station, the exit thickness, $(H_{\mathrm{M,ex}})_f$, becomes

$$(H_{\mathrm{M,ex}})_f = (H_{\mathrm{M,en}})_f - \Delta H_{\mathrm{M},i} \tag{6}$$

This method of exit-thickness adjustment reserves the ratio of thickness reduction between the n^{th} station and all 2^{nd} to N-1^{th} stations, which gives better results than simply averaging.

IV. Results and Discussion

A. Reduced Work Roll Temperature and Water Flow

The logarithmic relationship between reduced work roll temperature and water flow for 6-stand finishing mill is found

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:8, No:7, 2014

for each station, as shown in Fig. 2. Then the relationship is used to calculate the reduced temperature with data from actual cooling. The adjusted water flow is suggested such that the calculated reduced temperature stays almost the same, with the difference about 0.2 to 4.1% as shown in Table I, in which temperatures seem the same with two significant numbers displayed. This adjustment is more effective as the water flow is reduced by 8.5 to 9.6% as shown in Table II. This suggests that the relationship found can be used as a quick guideline for more effective work roll cooling although more experimental investigation should be done for verification.

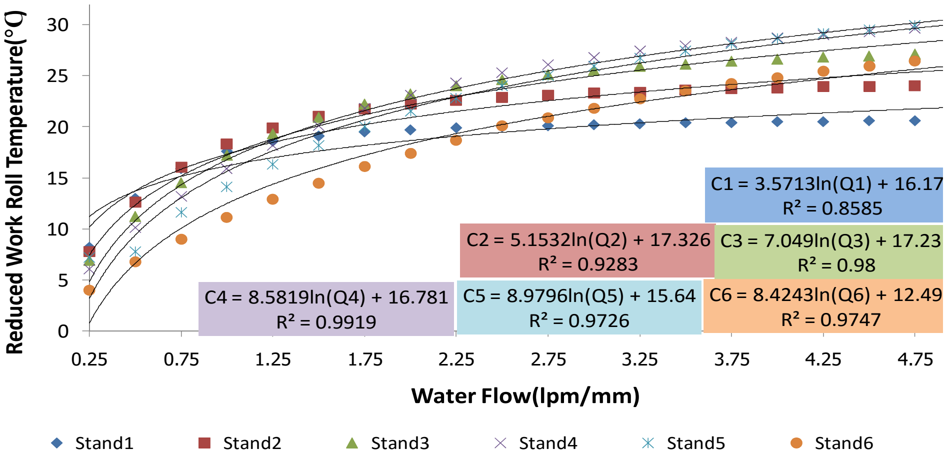

Fig. 2 Relationship between reduced work roll temperature and water flow for 6-stand finishing mill (Overall)

TABLE I
COMPARISON OF ACTUAL AND EFFECTIVE COOLING

Station No.	1	2	3	4	5	6
Actual Water Flow for Upper Work Roll (lpm/mm)	2.710	3.229	3.229	2.875	2.972	1.890
Actual Water Flow for Lower Work Roll (lpm/mm)	5.283	5.374	5.100	5.387	4.221	2.421
Calculated Reduced Temp. for Upper Work Roll (°C)	20	23	25	26	25	18
Calculated Reduced Temp. for Lower Work Roll (°C)	22	26	29	31	29	20
Adjusted Water Flow for Upper Work Roll (lpm/mm)	2.43	2.73	2.81	2.77	2.69	1.85
Adjusted Water Flow for Lower Work Roll (lpm/mm)	4.14	4.89	4.95	4.95	4.19	2.30
Calculated Reduced Temp. for Upper Work Roll (°C)	20	23	25	26	25	18
Calculated Reduced Temp. for Lower Work Roll (°C)	22	26	29	31	29	20
Temperature % Difference for Upper Work Roll	2.1%	3.7%	3.8%	1.2%	3.5%	1.0%
Temperature % Difference for Lower Work Roll	4.1%	1.9%	0.7%	2.3%	0.2%	2.2%

TABLE II
COMPARISON OF ACTUAL AND EFFECTIVE COOLING

Use of Water	Actual	Effective	% Difference
Water Flow for Upper Work Roll (lpm/mm)	16.90	15.28	9.6%
Water Flow for Lower Work Roll (lpm/mm)	27.79	25.42	8.5%

Another relationship between reduced work roll temperature and water flow for 6-stand finishing mill is found at the low flow region (less than 1.5 lpm/mm) to better describe the behavior in this region, as shown in Fig. 3. This region is chosen because most of the experimental data are in this region. Then the actual temperature reduced by cooling is used to calculate the suggested water flow and compare to the actual water flow, as shown in Table III. Most actual reduced temperatures in Table III are quite less than calculated reduced temperatures in Table I could be due to loss or ineffectiveness in actual cooling.

TABLE III
COMPARISON OF SUGGESTED AND ACTUAL WATER FLOW FOR 6 STAND FINISHING MILL

Station No.	1	2	3	4	5	6
Max Temperature for Upper Work Roll (°C)	26	17	13	17	14	14
Calculated Water Flow for Upper Work Roll (lpm/mm)	4.084	0.863	0.581	1.108	0.941	1.560
Max Temperature for Lower Work Roll (°C)	25	14	14	19	10	13
Calculated Water Flow for Lower Work Roll (lpm/mm)	3.480	0.579	0.660	1.430	0.504	1.314
Total Calculated Water Flow(lpm/mm)	7.564	1.441	1.241	2.538	1.445	2.875
Actual Water Flow (lpm/mm)	7.310	8.085	8.997	7.039	5.908	4.995

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:8, No:7, 2014

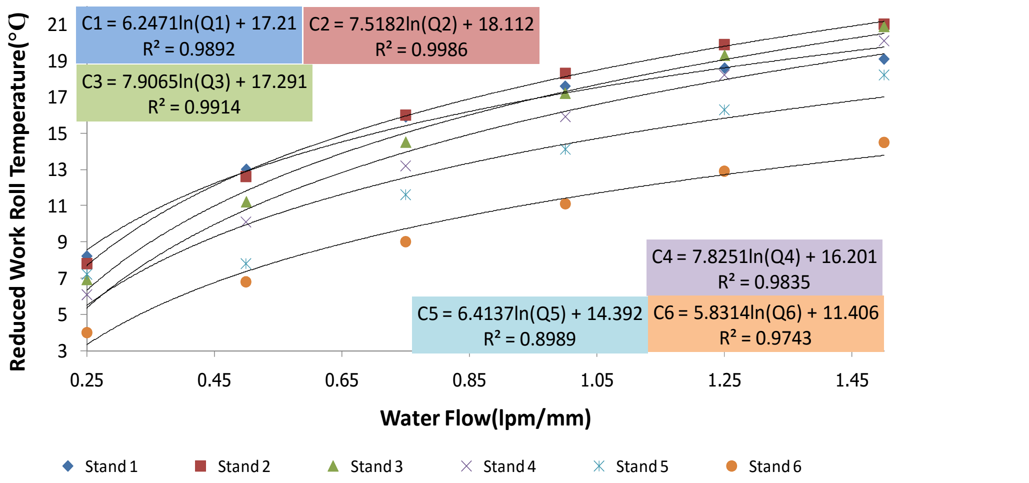

Fig. 3 Relationship between reduced work roll temperature and water flow for 6-stand finishing mill (Flow less than 1.5 lpm/mm)

B. Reduced Work Roll Temperature and Water Flow

The logarithmic relationship between reduced work roll temperature and water flow for 5-stand finishing mill is found for each station, as shown in Fig. 4, and the relationship for the low flow region is shown in Fig. 5. Then the actual temperature reduced by cooling is used to calculate the suggested water flow, as shown in Table IV. Then the logarithmic relationship between reduced work roll temperature and water flow for 4-stand finishing mill is found for each station, as shown in Fig. 6, and the relationship for the low flow region is shown in Fig. 7. Then the actual temperature reduced by cooling is used to calculate the suggested water flow, as shown in Table V.

Results suggest that the reduction of finishing-mill stands is possible since the amount of calculated water flow is comparable to the 6-stand case with satisfied quality of the product. This could greatly reduce construction, operation, and maintenance costs. The calculated water flow of the 4-stand case is less than the 5-stand case could be due to more effective heat transfer. Since in the 4-stand case each station has to carry more loads that create greater heat, heat transfer becomes more efficient due to the greater temperature difference.

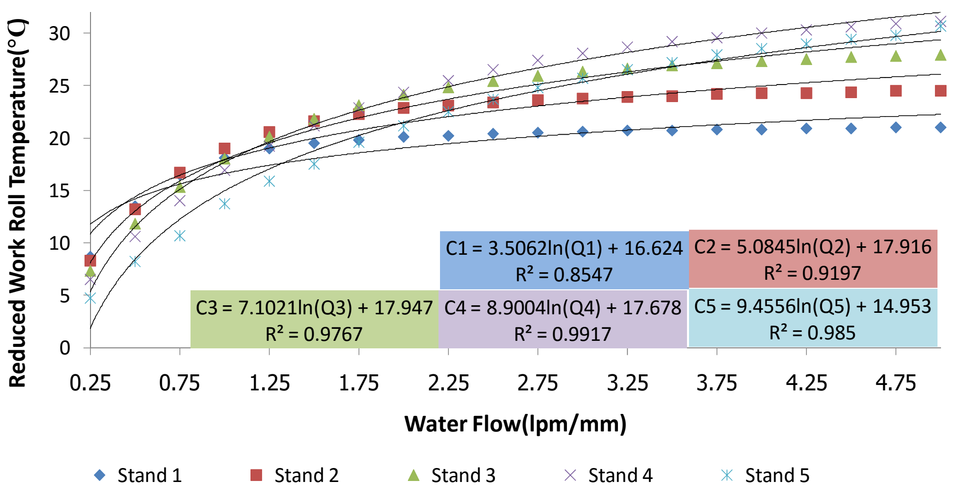

Fig. 4 Relationship between reduced work roll temperature and water flow for 5-stand finishing mill (Overall)

TABLE IV
COMPARISON OF SUGGESTED AND ACTUAL WATER FLOW FOR 5-STAND FINISHING MILL

Station No.	1	2	3	4	5
Max Temperature for Upper Work Roll (°C)	26	17	13	17	14
Calculated Water Flow for Upper Work Roll (lpm/mm)	3.834	0.7924	0.5368	0.9852	1.017
Max Temperature for Lower Work Roll (°C)	25	14	14	19	10
Calculated Water Flow for Lower Work Roll (lpm/mm)	3.262	0.5341	0.6067	1.256	0.5847

Total Calculated Water Flow(lpm/mm)	7.097	1.326	1.144	2.241	1.602

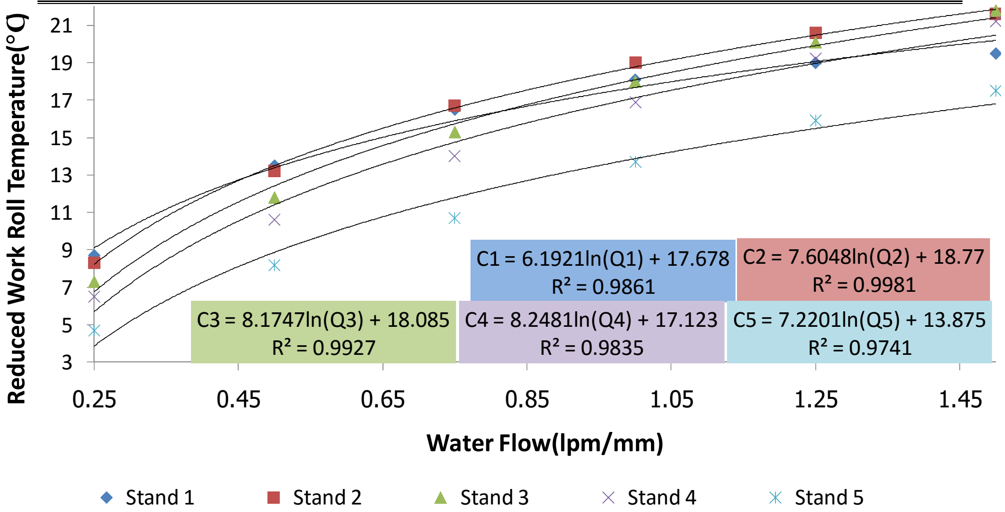

Fig. 5 Relationship between reduced work roll temperature and water flow for 5-stand finishing mill (Flow less than 1.5 lpm/mm)

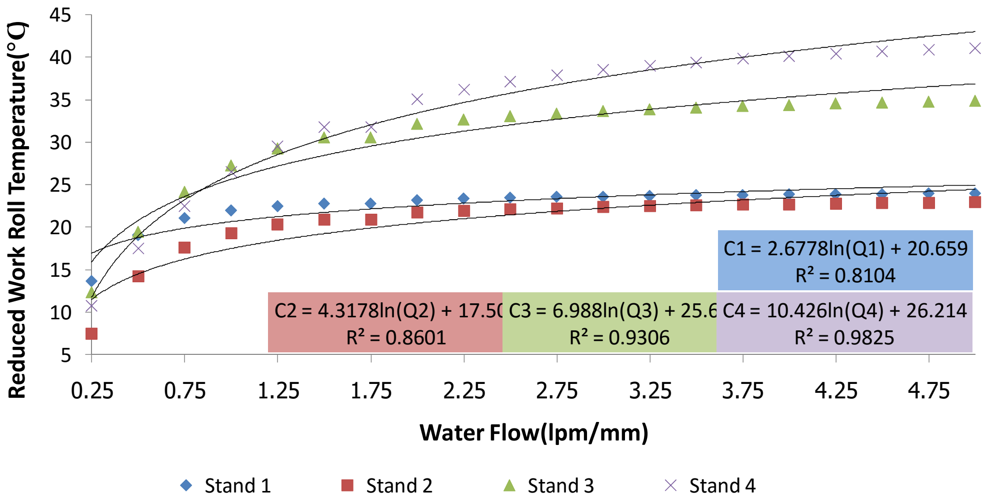

Fig. 6 Relationship between reduced work roll temperature and water flow for 4-stand finishing mill (Overall)

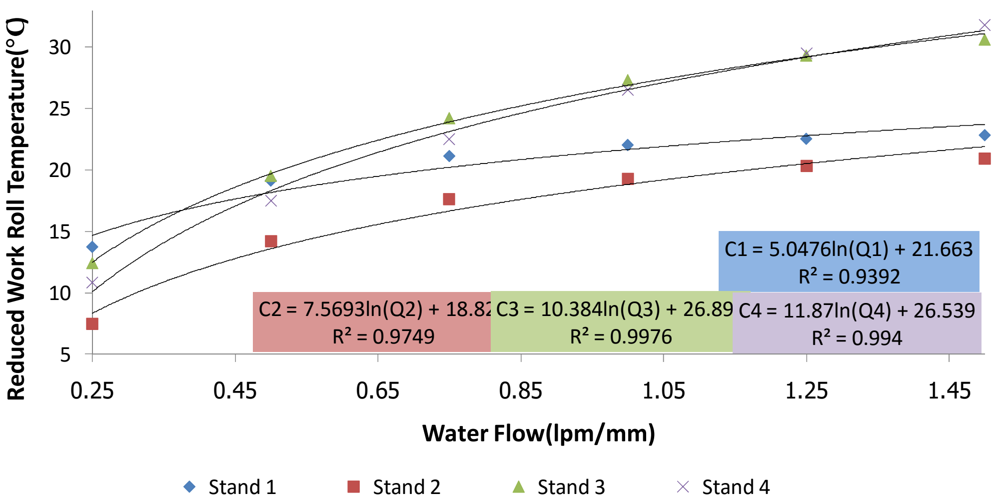

Fig. 7 Relationship between reduced work roll temperature and water flow for 4-stand finishing mill (Flow less than 1.5 lpm/mm)

TABLE V
COMPARISON OF SUGGESTED AND ACTUAL WATER FLOW FOR 4-STAND FINISHING MILL

Station No.	1	2	3	4
Max Temperature for Upper Work Roll (°C)	26	17	13	17
Calculated Water Flow for Upper Work Roll (lpm/mm)	2.361	0.7856	0.2624	0.4477
Max Temperature for Lower Work Roll (°C)	25	14	14	19
Calculated Water Flow for Lower Work Roll (lpm/mm)	1.937	0.5285	0.2889	0.5299
Total Calculated Water Flow(lpm/mm)	4.298	1.314	0.5514	0.9776

This study only observes the reduced temperature of the work roll but not the work roll temperature; therefore, it cannot monitor the health of work roll or verify its life-cycle. Nonetheless, the study gives a quick, systematic adjustment for hot strip processing and demonstrates that the quick guideline for the effective work roll cooling can be obtained.

ACKNOWLEDGMENT

The authors would like to express our gratitude to Sahaviriya Steel Industries PLC for experimental data and Integrated Manufacturing System Research Center (IMSRC) for HSMM software.

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