Advancements in Strip Temperature Modeling and Control for Hot Strip Mills

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ABSTRACT

In recent years, attention has been paid to measuring the temperature at the sides of the strip to prevent edge defects such as edge cracks and mixed grains in steel sheet production. Past practice has been to measure temperatures at a single point in the center of the strip, but scanning pyrometers are gradually being introduced. Similarly, in hot rolling temperature control, it is desired to calculate not only the temperature at the strip center, but also the temperature profile in the width axis. This paper discusses one aspect of process technology improvement for hot strip mills - strip temperature modelling and control. A finite difference method (FDM) is used to calculate the strip temperature distribution in each length element being rolled, based on time, temperature distribution and surface energy fluxes. Previously, a one-dimensional FDM (1D-FDM) was used where the distribution was originally modelled only in the thickness axis. Due to improvements in computing power, we now use a two-dimensional FDM (2D-FDM) which models both the thickness and width axis to estimate the temperature profile and drop at the strip edges. It is possible to switch between 1D and 2D FDM individually for each roughing or finishing mill zone and for the run-out table cooling zone. Some examples of on-line calculation results of the FDM temperature model are shown and the characteristics of the temperature distributions are discussed. In addition, the 2D-FDM can be calculated at "on-line". This allows high performance control of devices such as edge heaters and edge masks, which can be used to control the temperature in the width axis during actual hot strip mill rolling. It is useful to monitor the temperature profile using 2D-FDM calculation even where a scanning pyrometer is not equipped.

Keywords: Hot Strip Mill, Process control, Temperature model, 2D-Finite difference method, Online prediction calculation

INTRODUCTION

Today, rapid advances in electronics and IT technologies have led to rapid progress in making products and devices smarter. In addition, the transition to smart factories through the so-called IoT, which monitors the real world, collects data on objects to be managed, and transmits the data to analysis systems, is also progressing rapidly. To realize a smart factory, it is necessary to start with the optimization of individual devices, then the optimization of the production line, and finally the optimization of the entire factory. This optimization requires advanced data analysis. To achieve advanced analytics, conventionally dispersed data must be linked, and analysis methods must be used according to the situation to extract valuable knowledge from it for agile decision making. This will require a shift from conventional methods based on human judgment to methods using advanced analytics, such as optimization through simulations based on objective data, and cyber-physical systems (CPS) are expected to play an increasingly important role.

To realize CPS and advanced simulation in steel rolling, we require advanced process models and control technologies. These technologies are key to achieving stable rolling and high-performance control to produce stronger, lighter, and more decarbonized steel sheets. Temperature control is particularly important because it is a major determinant of the mechanical properties of the final product, the steel sheet[1,2]. The material temperature transition determines the deformation resistance and mechanical properties and affects the magnitude of rolling force and torque[3,4]. Since all setup controls depend on material temperature, accurate calculation of material temperature throughout the line is essential for precise process control.

From around 2000[5-9] until now, one-dimensional temperature models that solve for the temperature distribution in the thickness axis using the finite difference method have been applied to hot rolling lines, especially for ROT cooling. However, more recently, in order to prevent edge defects such as edge cracks and grain inclusions in steel sheet production, attention has been paid not only to simply monitoring the temperature in the middle of the width axis, but also to measuring the temperature at the edge of the plate in the width axis.

This paper discusses one aspect of process technology improvement in hot strip mills: strip temperature modeling and control. We have now developed a technique that uses a two-dimensional Finite Difference Method (2D-FDM) to estimate the temperature profile and drop at the strip edge[10]. The temperature model can be switched between 1D-FDM and 2D-FDM at each zone of roughing, finishing, and runout table cooling. The 2D-FDM can be calculated online of devices such as edge heaters and edge masks during actual hot strip mill rolling. This paper introduces the 2D-FDM.

OBJECTIVE PROCESS

Figure 1 shows the configuration of the hot rolling mill used for the production of flat products under investigation. Slabs are subjected to a reheating process in a furnace, reaching temperatures of approximately 1250°C. The slab surface is descaled. The slab is then subject to multiple passes in a roughing mill and edger, with the objective of attaining the desired thickness and width. Following the processes of cropping the head and tail, and the application of a second descaling, the transfer bar (as it is now designated) is transferred to the finishing mill, where it is rolled to the desired product thickness, profile, and flatness. A finishing mill temperature control system is used to attain the desired temperature at the finishing mill exit (FDT). FDT is a pivotal parameter in determining the quality of the product strip. The strip is then cooled to the target coiling temperature on the run out table and subsequently coiled at the down coiler. Certain steels need the implementation of cooling trajectory control schemes in order to meet their metallurgical requirements. In the past, temperatures were measured at a single point in the center of the width axis. However, scanning thermometers are gradually being introduced, and attention is being paid to measuring the temperature at the edge of the strip in the width axis to prevent edge defects such as edge cracks and mixed grains in steel sheet production. Thus, it is very important to establish highly accurate temperature monitoring and control.

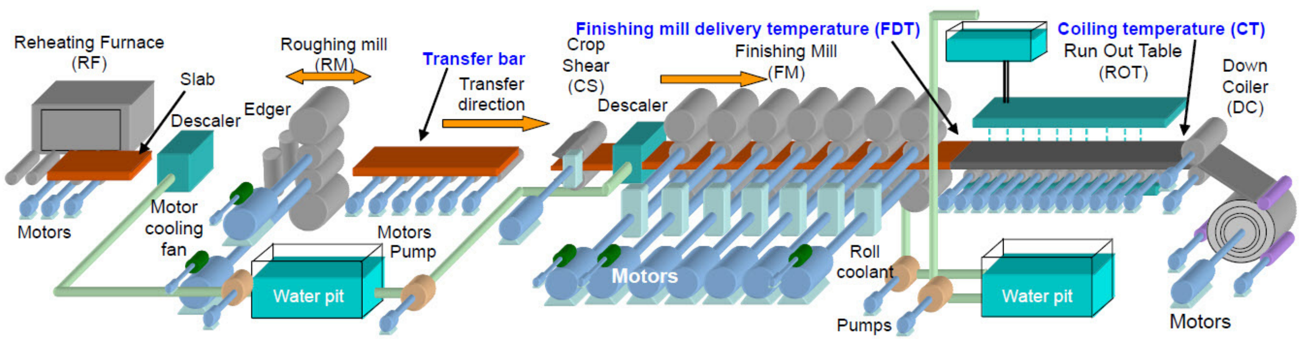

Figure 1. Configuration of hot rolling mill and material

ANALYSIS OF TEMPERATURE CHANGE USING 1D-FDM MODEL

The initial generation of strip temperature prediction models comprised a single degree of freedom, with a uniform temperature distribution along the thickness and width axes of the strip. It has been determined that the calculated temperature in this model is equivalent to the mean temperature of the cross-section of the strip. The following formula is employed to calculate the mean temperature across the strip:

$$\Delta T_{avg} = \frac{\Sigma Q^k}{\rho C_p V} \Delta t \tag{1}$$

where,

ΔT_{avg} : Average temperature change of cross section
ΣQ^k : Sum of heat transfer by radiation, convection, etc.
ρ : Density of the strip
C_p : Specific heat of the strip
V : Volume of the cross section of the strip (unit length)
Δt : Elapsed time

In the context of the hot strip mill operation, a multitude of heat transfer mechanisms are in effect, including radiation, convection of air or water, and conduction to the roll. These phenomena collectively influence the thermal dynamics of the strip. The surface of the strip exhibits a high degree of variability in its boundary conditions, and the temperature of the surface undergoes rapid changes in comparison with the internal temperature of the strip. Top surface temperature prediction was subject to subsequent correction based on measurement values derived from multiple pyrometers installed along the mill line. It is imperative to calculate the average temperature, given its role in determining properties such as deformation resistance. To address this, the surface temperature, as measured by the pyrometer, must be used to estimate the average temperature. This is further compounded by the existence of variable temperature difference between the top surface and the interior of the rolled material. The difference was found to vary according to thickness, and was not modelled.

In recent years, advancements in process computer speed and performance have facilitated the application of a one-dimensional finite difference method (1D-FDM) to setup predictions and online temperature control. The 1D-FDM model calculates the temperature distribution in the thickness axis as a dynamic function of time. The transfer of heat by radiation, convection through spray water and air, conductive heat transfer to rolls, and the generation of heat by friction in the roll bite are all considered at the surface of the strip. In the inner nodes, the generation of heat by deformation in the roll bite, latent heat of metal phase change, and internal heat conduction from adjacent nodes are considered. The calculation of both surface temperature and average temperature is performed by the FDM, with subsequent recalibration by pyrometers.

Figure 2 illustrates the fundamental concept of the 1D-FDM temperature model employed within the context of a hot strip mill .

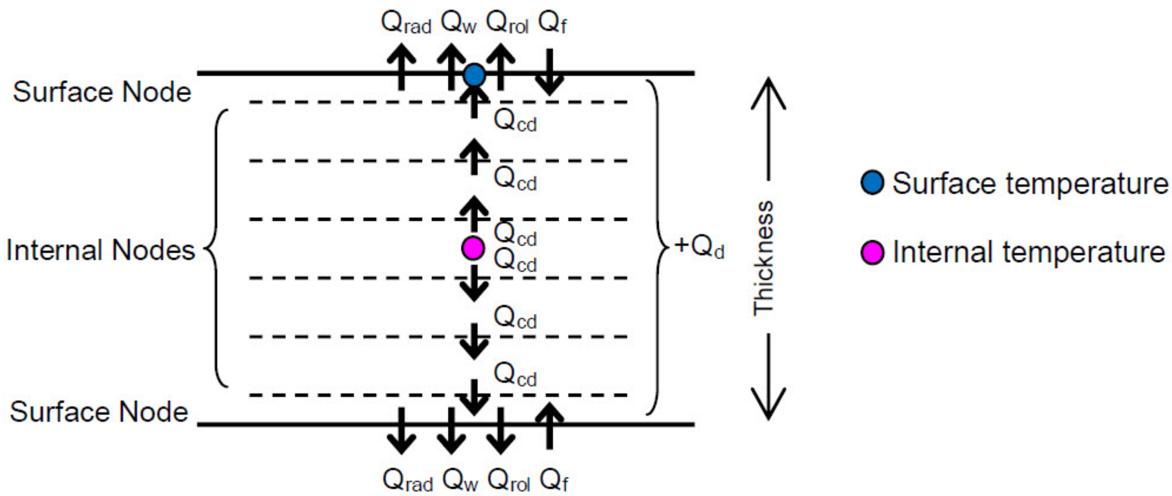

Figure 2. 1D-FDM temperature model

where,

Q_{rad} : Heat transfer by radiation from surface
Q_w : Heat transfer by convection to spray from surface
Q_{rol} : Heat transfer by conduction to roll from surface
Q_f : Heat transfer by friction into surface
Q_d : Heat generation by deformation inside strip
Q_{cd} : Heat transfer by conduction

The temperature change rate of a node in 1D-FDM model is calculated as follows.

$$\Delta T_i = \frac{\sum Q_i^k}{\rho C_p V_i} \Delta t \quad (2)$$

where,

ΔT_i : Temperature change of i-node
$\Sigma Q^k{}_i$: Sum of heat transfer by radiation, convection, conduction, etc. of i-node
ρ : Density of the strip
Cp : Specific heat of the strip
V_i : Volume of the cross section of i-node

Δt : Elapsed time

In order to calculate the distribution of temperature along the thickness axis using the finite element method, the heat conduction between nodes is considered based on the Fourier formula presented below.

where,

$$Q_{cd} = -kA\frac{\partial T}{\partial x} \tag{3}$$

k : Thermal conductivity
A : Area between nodes
x : Distance between nodes

As shown in Figure 3, the online calculation of the strip is facilitated by the 1D-FDM temperature model. In this instance, the temperature calculation is demonstrated for the process of roughening and finishing rolling from a slab with a thickness of 250 mm to a product strip thickness of 3 mm. The surface temperature of the rolled strip is subject to significant fluctuations, which can be attributed to the variation in the boundary conditions. The temperature at the center of the rolled strip decreases more steadily, with the rate of decrease increasing as each stand reduces the thickness of the strip. At the final finishing delivery temperature (FDT), the surface temperature and the center temperature are almost equal to each other, and a substantially uniform temperature distribution is obtained. In the calculation of the deformation resistance of each stand, the average temperature of all nodes is used. A reasonable deformation resistance calculation is imperative for the prediction of rolling force and torque.

The number of nodes modelled in the thickness axis is reduced as the thickness is reduced by rolling. Furthermore, the elapsed time step (t) in the heat conduction equation is subject to alteration in accordance with changes in the boundary conditions that govern the transportation of the rolled material. It is long in air-cooled regions (in the order of 10-1s), while it is short in water-cooled and rolling regions (in the order of 10-2s). Consequently, the number of calculation steps is reduced without compromising the accuracy of temperature calculations, thereby minimizing the calculation load on the online computer. With regard to Figure 2, 394 steps in rougher rolling and 335 steps in finishing rolling are taken for the purpose of temperature calculation.

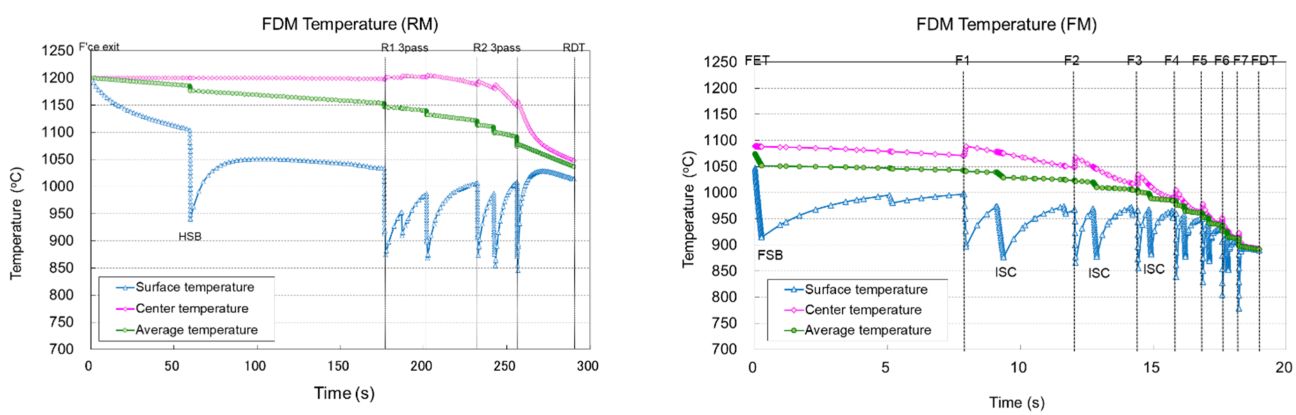

Figure 3. 1D-FDM Temperature model calculation (Left: Rougher rolling, Right: Finishing rolling)

The FDM temperature model has the advantage that it enables the separate management of heat transfer on the top and bottom sides. In the calculation of the temperature of the top and bottom surfaces, the top/bottom asymmetry in the runout table water-cooling spray pattern is taken into consideration.

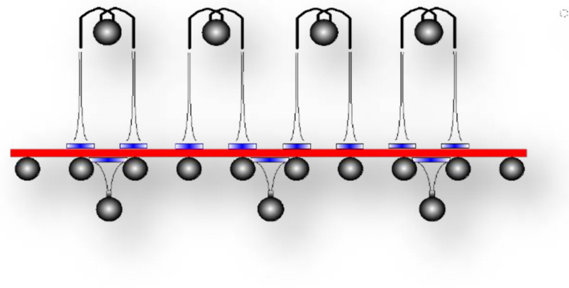

Figure 4. Asymmetric water cooling between top and bottom side

EXPANDED TEMPERATURE CALCULATION BY 2D-FDM MODEL

The uniformity of temperature distribution in the strip width direction is of paramount importance in ensuring the uniformity of mechanical properties. A substantial decrease in the edge temperature can result in various defects, including edge crack, mixed grain size, or duplex grain structure. An expanded two-dimensional FDM (hereinafter referred to as "2D-FDM") temperature calculation has been developed, with nodes in both the width and thickness axes. The transfer of radiation and convection heat from water and air to the surface nodes at the side edge is the focus of this study. Heat conduction in two axes is regarded as internal nodes.

As illustrated in Figure 4, the 2D-FDM temperature model conceptualizes the relationship between temperature and the physical properties of the material. In the width axis, nodes are categorized into two distinct types: edge nodes and body nodes. It is evident that the distance between the edge nodes is minimal (dy), on account of the substantial temperature, temporal and spatial gradients that are present at the periphery. Conversely, the body nodes are separated by greater distances (yb) due to the diminished temperature gradient. In the thickness axis, the nodes are divided in the same way as in the 1D-FDM model. It has been demonstrated that the utilization of disparate distance spacings on the width axis results in a reduction of the total number of nodes necessary, consequently diminishing the calculation load of the online computer.

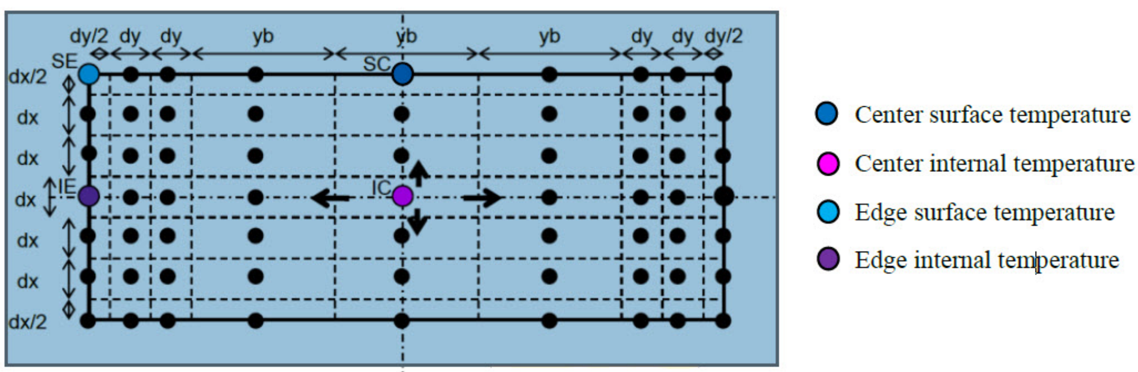

Figure 5. Expanded 2D-FDM temperature model

The calculation of the temperature change rate of a node in the 2D-FDM model is as follows:

$$\Delta T_{i,j} = \frac{\Sigma Q_i^k + \Sigma Q_j^k}{\rho C_p V_{i,j}} \Delta t \tag{4}$$

where,

$\Delta T_{i,j}$: Temperature change of (i, j) node
$\Sigma Q^k{}_i$: Sum of heat transfer by radiation, convection, conduction, etc. in thickness axis of (i, j) node
$\Sigma Q^k{}_j$: Sum of heat transfer by radiation, convection, conduction, etc. in width axis of (i, j) node
ρ : Density of the strip
C_p : Specific heat of the strip
$V_{i,j}$: Volume of the cross section of (i, j) node
Δt : Elapsed time

As described in Figure 6, the 2D-FDM temperature model can be utilized to calculate the temperature in the width axis online. Despite the variation in thickness and width, the temperature drop is observed to be concentrated within a range of approximately 150 mm from each edge. It is imperative to ensure that the node spacing in the 2D-FDM model is meticulous at the edges, with a margin of error of 100 mm, while allowing for a certain degree of variability in the central region. In practice, three equally sized nodes in the center are sufficient for the online calculation.

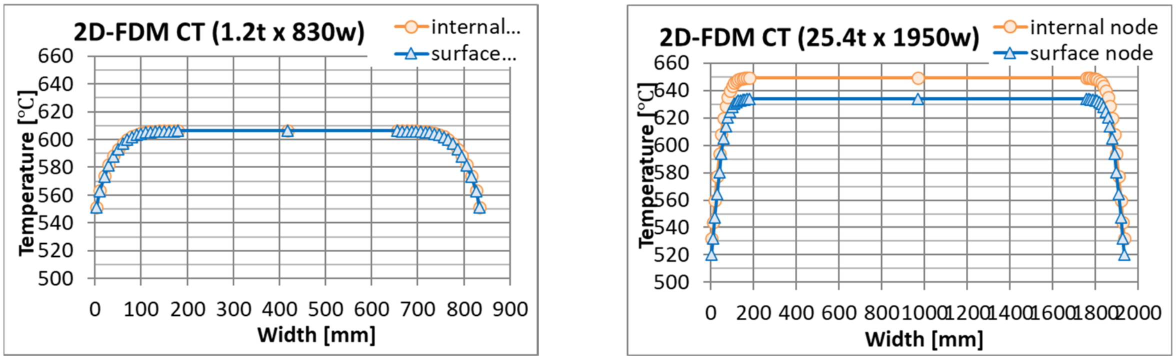

Figure 6. 2D-FDM CT temperature calculation along width (Left: thickness 1.2mm, Right: thickness 25.4mm)

As depicted in Figure 7, the 2D-FDM temperature calculation of the runout table (ROT) cooling process is demonstrated, whereby the temperature is reduced from the finishing delivery temperature (FDT) to the coiling temperature (CT). In this instance, the water cooling of the ROT laminar spray is initiated from bank #1 to #3 for FF control, and from #14 to #16 for FB control. In a region of water cooling by laminar spray, heat is lost quickly from the strip surface, and the temperature difference in the thickness direction increases. In a region of air cooling, the surface heat loss rate of the strip is reduced, and the temperature difference in the thickness direction is decreased by internal heat conduction. It is evident that there is a considerable alteration in the uniformity of internal temperature distribution in the thickness direction as the region transitions from water cooling to air cooling. Conversely, the temperature distribution in the width direction tends to maintain uniformity from center to edge, despite changing cooling conditions. It is evident that the CT position exhibits a variation in temperature across the width axis, with a range of approximately 100°C from the center to the edge of the strip.

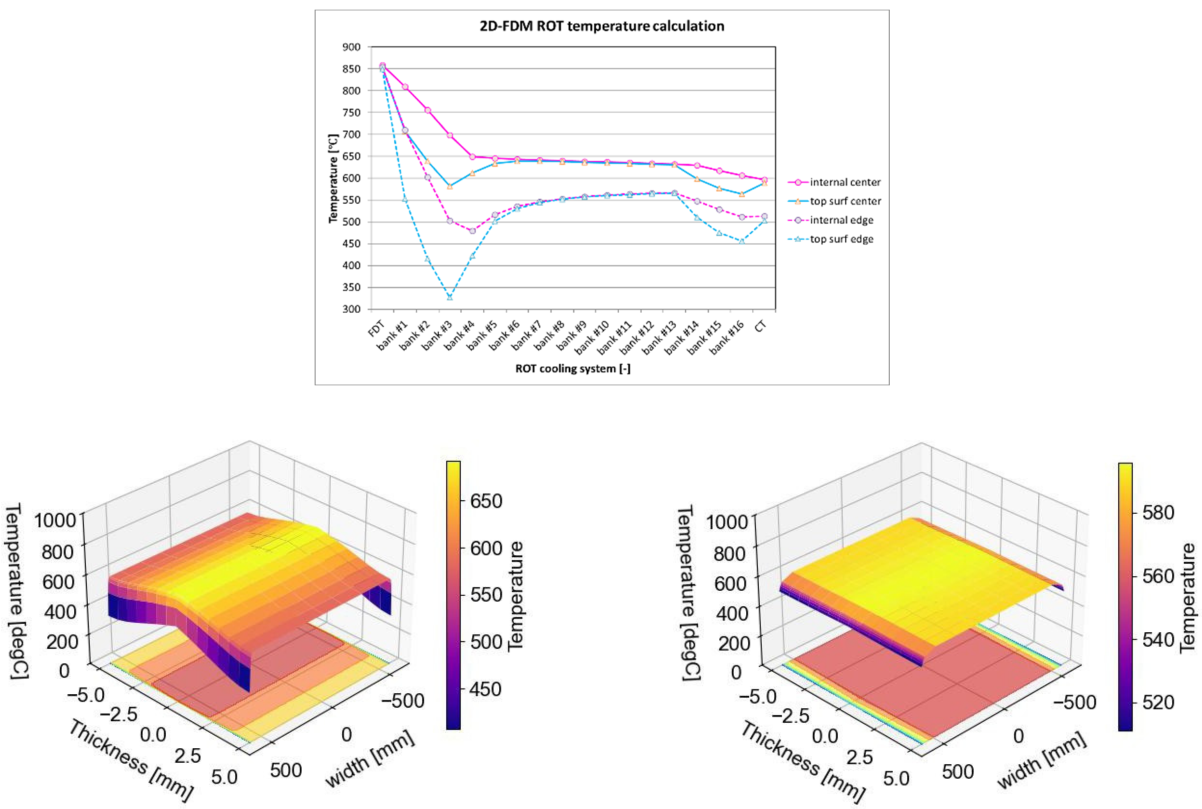

Figure 7. 2D-FDM ROT temperature calculation
(Top: from FDT to CT, Bottom-left: after bank #3 cooling, Bottom-right: CT)

APPLICATION TO ONLINE COMPUTER OF 1D/2D FDM TEMPERATURE MODEL

The recent advancements in the field of computer technology, marked by increased processing speeds and enhanced performance capabilities, have paved the way for the integration of FDM temperature calculation methodologies within the realm of online control systems.

It is evident that a 2D-FDM temperature model must calculate a greater number of nodes than a 1D-FDM for a given cross section of the strip. In order to reduce computing load, modifications have been made to the number of nodes based on thickness, the elapsed time step based on boundary condition, and the different node distance between body and edge in width axis. Consequently, the online calculation time for the 2D-FDM temperature model does not exceed the time sufficient for the rougher mill set-up (RSU) and finishing mill set-up (FSU), and the dynamic feed-forward and feedback control calculation of finishing delivery temperature control (FDTC) and coiling temperature control (CTC) do not exceed sufficient time for control. As illustrated in Figure 8, this process model and control system configuration is a typical example. The FDM temperature calculation of the rolled piece is applied throughout the piece's transportation from furnace delivery to coiler entry. Each model function has the capacity to alternate between 1D-FDM and 2D-FDM, and the temperature mapping of the cross-section at the point of connection between functions is converted between 1D and 2D-FDM. The heat energy in a cross-section of the piece is maintained at the conversion.

Figure 9 shows an example of 2D-FDM overall temperature calculation from furnace drop-out to down coiler entry. This online calculation time for the 2D-FDM temperature model also does not exceed the time sufficient for the rougher mill set-up (RSU) and finishing mill set-up (FSU), and the dynamic feed-forward and feedback control calculation of finishing delivery temperature control (FDTC) and coiling temperature control (CTC) do not exceed sufficient time for control.

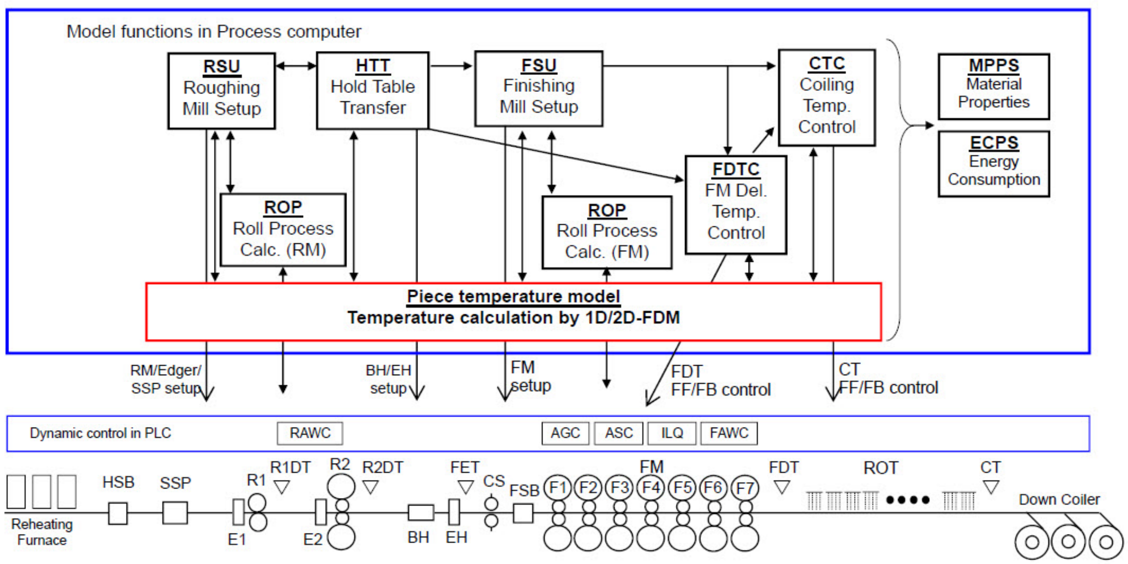

Figure 8. Typical configuration of online process model and control system for conventional hot strip mill

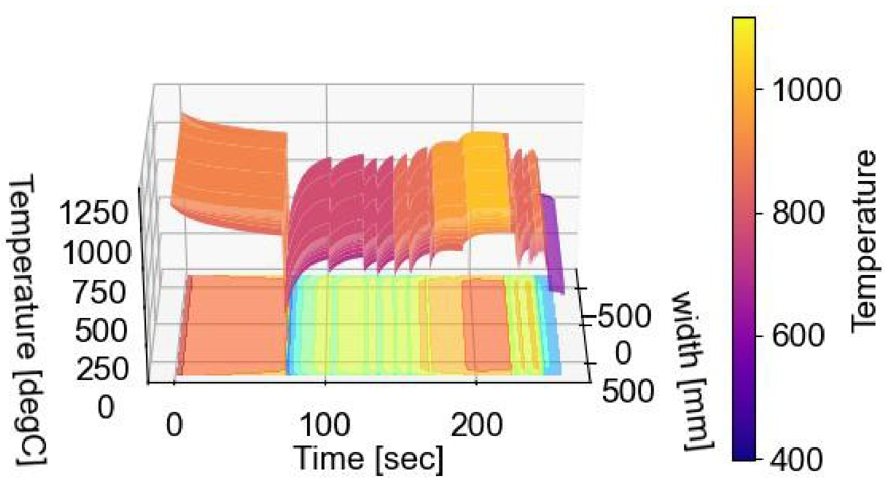

Figure 9. 2D-FDM overall temperature calculation from furnace drop-out to down coiler entry

CONCLUSION

The advent of enhanced computer processing capabilities has paved the way for the utilization of the finite difference method (FDM) in temperature prediction and online control applications. The 1D-FDM model is a numerical method that calculates the temperature distribution along the thickness axis over time, taking into account heat transfer mechanisms at the surface and internal nodes. The model is recalibrated using pyrometers. The phenomenon of heat conduction between nodes is predicated on the application of Fourier's formula.

The 2D-FDM model extends the scope of temperature calculations to encompass nodes along both the width and thickness axes. Edge nodes are positioned with minimal spacing, a consequence of substantial temperature gradients, whilst body nodes are positioned at greater distances from one another. Notwithstanding the presence of variations in thickness and width, the phenomenon of temperature drop is observed to be concentrated in proximity to the edges.

Recent advancements in the field of computer technology have resulted in the integration of finite element method (FDM) temperature calculations into online control systems, with a transition between one-dimensional (1D) and two-dimensional (2D)-FDM models. Adjustments to node numbers, elapsed time steps, and node distances have been shown to reduce computing load, ensuring efficient online calculations.

Recent technological advancements, including the integration of edge heaters, edge masking and scan pyrometers, have led to the emergence of 2D-FDM temperature calculation as a pivotal technological capability. It is advantageous to monitor the temperature profile by 2D-FDM calculation even in the absence of a scan pyrometer, and to study the rolling process conditions to ensure uniform material properties.

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