DEVELOPMENT AND VERIFICATION OF A SYSTEM FOR 2D ANALYSIS OF COUPLED MAGNETO–THERMAL PROBLEMS

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In rolling systems with direct transmission it is strongly desired that the temperature distribution of the metal billet is uniform. For that purpose, an optimal induction heating system must be developed. In this paper, a new 2D simulation system for analysis of magneto-thermal coupled problem inside the billet is presented. This system comprises two main routines: 2D edge-based finite element analysis for eddy current computation and 2D non-liner node-based finite element analysis for thermal field computation. The proposed system includes the influence of the billet's movement and temperature changes in the moving direction that is perpendicular to the analysis field, providing accurate quasi-3D computation. The obtained results show very good agreement with previously computed results using 3D simulation system with significantly less computational cost.

K e y w o r d s: Induction Heating, eddy-current analysis, temperature analysis, finite element method.

1 INTRODUCTION

Rolling systems with direct transmission strongly require that the temperature distribution of the metal billet is uniform. To aid in this process an additional induction heating system must be developed. A 3D system for the simulation of the magneto-thermal coupled phenomena and which provided a highly accurate results has already been proposed [1]. However, due to the model complexity, the 3D system requires a large amount of input data and long computation time which significantly aggravates its advantages. Therefore, the development of more simple 2D simulation system which could provide fast and accurate simulation of the analyzed phenomena at least in the initial design stage of the analysis is strongly desirable.

In this paper, the authors present a newly developed 2D simulation system with the above mentioned features. Because in the analyzed model source currents flow in the same xy-plane as the model, for the simulation system we adopt 2D edge-based finite element method, which further decreased the computational time [2]. Similarly to the already developed 3D simulation system, due to the nonlinearity of the heat transfer, heat conductivity and specific heat coefficients, we adopt nonlinear node-based finite element method for the thermal field analysis. Additional feature of the proposed system is that it includes the influence of the billet's movement and temperature changes in the moving direction that is perpendicular to the analysis field, providing accurate quasi-3D computation. In what follows, first we briefly describe the basis of the developed 2D simulation system and its features. Next, we describe the analysis model and the obtained results. Finally the validity of the proposed system is confirmed by comparing its results with previously obtained results using the 3D simulation system.

2 INDUCTION HEATING SYSTEM

A simple model of the analyzed rolling system with direct transmission is presented in Fig. 1. It takes approximately 1–2 minutes to roll a billet with length of 5 [m], during which its temperature, especially along its surface becomes nonuniform. Therefore, its surface temperature must be additionally risen using induction heating coils. The largest problem is to rise the billet temperature along its edges for which an optimal design of the induction coils must be considered. First step in the process of optimization of its design is to understand the eddy current and thermal field distributions inside the induction heating simulation system exactly.

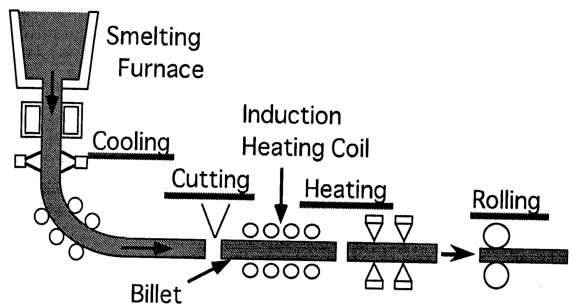

Fig. 1: Model of a rolling system with direct transmission.

The outline of the developed 2D simulation system is shown in Fig. 2. As can be seen from Fig. 2, t is the current analysis time, Δt is the analysis time step, and t_{max} is the final time of the analysis. The process starts with reading the input data which is essential for the analysis, such as coil location data, initial temperature data, etc. Next, it calculates the electric conductivity coefficients by using initial temperature distribution data, followed by the eddy-current analysis utilizing edge-based finite element method and the calculation of the generated thermal heat inside the billet due to the generated eddy-currents flow. Then the non-linear thermal field analysis with node-based finite element method is executed, taking the values for the generated heat as a heat source. This procedure is repeated until the time step reaches the final time step which is set in advance. If the final time step is not yet reached, it renews electric conductivity coefficients using obtained temperature distribution in

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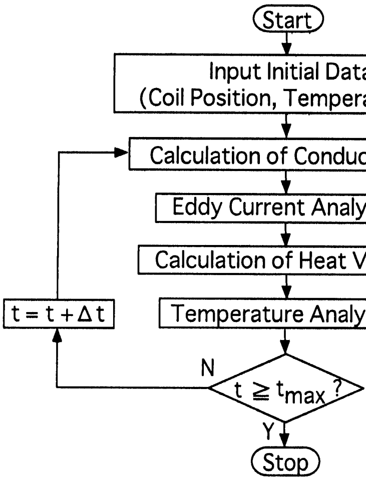


Fig. 2: Outline of the proposed 2D induction heating simulation system.

order to consider the temperature dependency of electric conductivity coefficients.

3 EDDY CURRENT ANALYSIS

As we already mentioned above, in the proposed 2D simulation system, we analyze a model which is perpendicular to the moving direction of the billet as shown in Fig. 3a. Therefore, it is necessary to consider surface flow of the source currents with source current density vectors J_x, J_y which lie inside the analysis xy–plane. As a result, utilizing of the 2D edge-based finite elements is very advantageous since these elements have unknowns which lie in the same plane with the model [2].

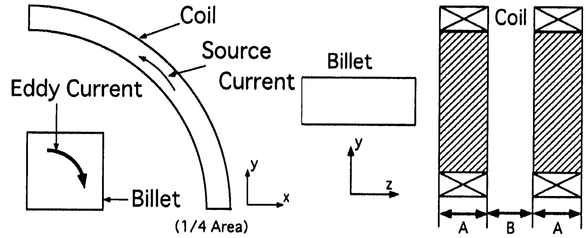
The governing equation for eddy-current magnetic field problem is

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\mathbf{D} \ , \tag{1}$$

where $\mathbf{H}$ is the magnetic field intensity vector, $\mathbf{J}$ is the source current density vector, $\mathbf{D}$ is the electric flux density and ω is the angular frequency. Using vector interpolation functions $\mathbf{N_i}$ and adopting the Galerkin's weighted residual procedure, Eq. (1)can be transformed into the following equation

$$\int\!\!\int_{S_e} \left(\frac{1}{\mu} \nabla \times \mathbf{N}_i \cdot \nabla \times \mathbf{A} - \omega^2 \epsilon^* \mathbf{N}_i \cdot \mathbf{A} - \mathbf{N}_i \cdot \mathbf{J} \right) dS = 0 \ , \tag{2}$$

where $\mathbf{A}$ is the vector potential, S_e is the area of triangle element, ϵ^* is the complex permittivity coefficient ($\epsilon^* = \epsilon - j\sigma/\omega$), and ϵ and σ are the permittivity and the electric conductivity coefficients respectively. After solution of the generated system of linear equations utilizing edge-based finite element method, the eddy-current values at each edge of the mesh could be obtained. To calculate the generated heat source value, first, the values of the eddy-current at each node are computed resulting in two components of eddy-currents at each node, J_x, and J_y, and the intensity value $J = \sqrt{J_x^2 + J_y^2}$.



(a) 2D model (b) Induction heating coil.

Fig. 3: Analyzed model.

4 TEMPERATURE ANALYSIS

In order to increase its surface temperature, billet moves inside the induction coils as shown in Fig. 3b. The generated heat value which is calculated using already obtained eddy-current values, during thermal field analysis is treated as the heat source, when the billet is inside the induction heating coil area (Area A). On the other side, when the billet is outside of the induction coil area (Area B), the heat source is not considered, and only the transfer of the already generated temperature distribution to its surroundings is analyzed. Again, by adopting the Galerkin's weighted residual procedure, the non-steady heat conductive equation is transformed as follows

$$\begin{aligned} G &= \left\{ \beta\,[K] + \frac{1}{\delta t}\,[C] \right\} \{T(t+\delta t)\} \\ &+ \left\{ (1-\beta)\,[K] - \frac{1}{\delta t}\,[C] \right\} \{T(t)\} - \{f\} = 0 \ , \end{aligned} \tag{3}$$

$$\begin{aligned} [K] &= \int_{S_e} (\kappa_x \frac{\partial \{N\}}{\partial x} \frac{\partial \{N\}^T}{\partial x} + \kappa_y \frac{\partial \{N\}}{\partial y} \frac{\partial \{N\}^T}{\partial y}) dS \\ &+ \int_l h_s \{N\} \{N\}^T dl \ , \end{aligned} \tag{4}$$

$$[C] = \int_{S_e} \rho c \{N\} \{N\}^T dS \ , \tag{5}$$

$$\{f\} = \int_{S_e} Q \{N\} dS + \int_l h_s T_\infty \{N\} dS \ , \tag{6}$$

where $T(t+\delta t)$ is the unknown temperature, $T(t)$ is the temperature at previous step, ρ is the density coefficient, c is the specific heat coefficient, κ_x, and κ_y are the thermal conductivity coefficients for x and y direction, respectively, h_s is the heat transfer coefficient, T_∞ is the temperature of surroundings and Q is the heat value. For solution of Eq. (3) we utilized the the Crank–Nicolson method with $\beta = 0.5$.

In the thermal field analysis, the heat source is computed using the eddy-current intensity values according to the following equation

$$\{Q\} = \frac{\rho}{2} \int\!\!\int_{S_e} \{\mathbf{J}\}^T \{N\} \{N\}^T \{\bar{\mathbf{J}}\} \{N\} dS \ , \tag{7}$$

where $\mathbf{J}$, and $\bar{\mathbf{J}}$ are the eddy-current density vector and its conjugate value and N is the interpolation function. The Eq. (7) is employed for calculation of the source heat values at each node of the finite element mesh.

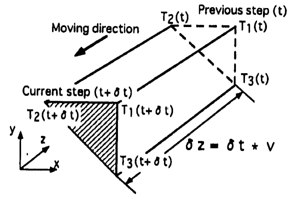


Fig. 4: Prism element.

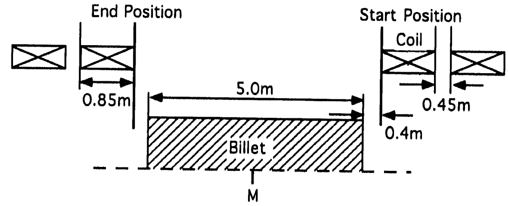


Fig. 5: Simulation model.

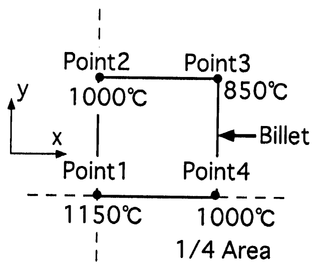


Fig. 6: Initial temperature distribution.

When the thermal field analysis is executed in 2D xy−plane, it cannot consider the z-direction of the heat conduction. However, to accomplish high accurate results, the z-direction of the heat conductivity should not be neglected. The proposed 2D simulation system includes the conduction of the heat in the z-direction utilizing 3D prism finite elements. The length of each prism finite element in the z-direction can be easily computed using the time step value δt and the speed of the billet v in the z-direction as shown in Fig. 4. This procedure enables consideration of the temperature changes not only in 2D space but even in the entire 3D space. Therefore, although the analysis is performed in 2D space, actually, a quasi-3D temperature analysis is executed. The numerical representation of the temperature distribution along z-direction using this prism finite element is given as

$$\int_{V_e} \kappa_z \frac{\partial\{N\}}{\partial z}\frac{\partial T}{\partial z} dV$$

$$= \kappa_z \int_{V_e} \frac{1}{\delta z} \left\{ \begin{array}{c} -L_1 \\ -L_2 \\ -L_3 \\ L_1 \\ L_2 \\ L_3 \end{array} \right\} \frac{T(t+\delta t) - T(t)}{\delta z} dxdydz$$

$$= \frac{\kappa_z}{\delta z} \int_{S_e} \left\{ \begin{array}{c} -L_1 \\ -L_2 \\ -L_3 \\ L_1 \\ L_2 \\ L_3 \end{array} \right\} \left[\{L_1 \quad L_2 \quad L_3\} \left\{ \begin{array}{c} T_1(t+\delta t) \\ T_2(t+\delta t) \\ T_3(t+\delta t) \end{array} \right\} \right.$$

$$\left. - \{L_1 \quad L_2 \quad L_3\} \left\{ \begin{array}{c} T_1(t) \\ T_2(t) \\ T_3(t) \end{array} \right\} \right] dxdy\,, \qquad (8)$$

where L_i are the area coordinates and V_e is the volume of the prism element. As can be seen from Fig. 4 the unknown values of the temperature at time step $t + \delta t$ can be computed using the already know values of the temperature at previous time step t.

5 SIMULATION MODEL AND RESULT

The simulation model which is used to simulate the temperature changes of the billet inside the induction heating coils is shown in Fig. 5. To facilitate the numerical analysis, instead of billet's movement, the proposed simulation system adopts static billet and moving induction coils, which from the physical point of view brings no differences in the final results. The velocity of the billet is 0.125 [m/s] and the computation time step was set to 1.0 [sec]. The initial temperature distribution of the billet before it enters the induction coil zone is given in Fig. 6. First, the initial temperature at four typical points (points 1 ∼ 4 in Fig. 6) is set, followed by setting of the initial temperature at other points inside the analysis domain utilizing linear interpolation. The source current which flows inside the induction coils has intensity of 25000 [A] and frequency of 1200 [Hz], while the temperature of the surroundings is set to $T_\infty = 20$ [°C].

The numerically obtained results using the proposed simulation system are given in Figs. 7, 8, and 9, for three typical points inside the analysis domain (points 1, 2, and 3 in Fig. 6), respectively. In each figure, three temperature records are given: one for the 3D analysis, and two for the 2D analyses with and without considering the z-direction heat conduction coefficient. For 3D analysis, the presented temperature record corresponds to the data obtained at cross-section plane M as shown in Fig. 5. As can be easily seen, the results obtained with the proposed 2D simulation system are in very good agreement with previously computed results using 3D simulation system. However, as can be seen from Table I, the computation time for one 2D analysis is several hundred times shorter than that of the 3D analysis, although in 3D simulation several eddy-current analysis are omitted when billet is in the zone where the changes of the magnetic field are negligible small. For example, for this model a total number of 20 steps out of 65 steps of eddy-current analyses are omitted.

Table I: Simulation time [min]

Type of analysis	3D	2D
Eddy-currents distribution	2044	0.383
Temperature distribution	52	0.217

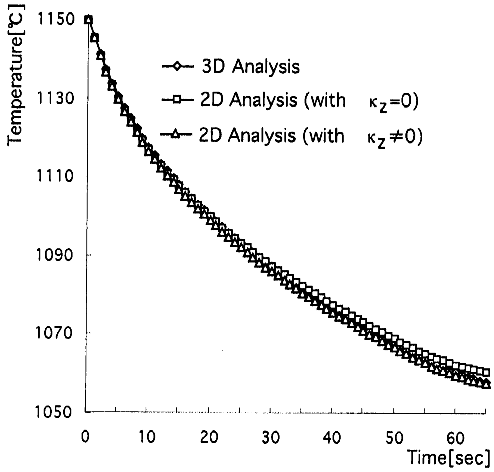


Fig. 7: Temperature record at point 1.

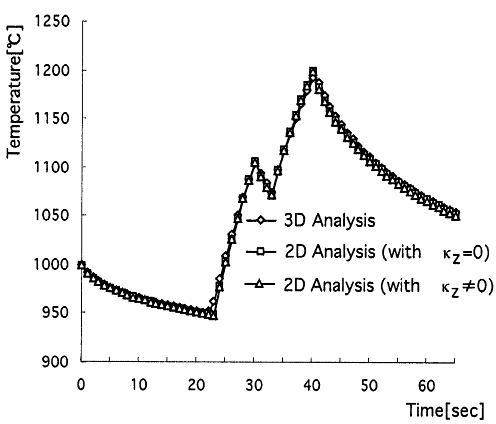


Fig. 8: Temperature record at point 2.

6 CONCLUSION

For the initial step of design optimization of the induction heating system and its evaluation a new 2D simulation system for analysis of the coupled magneto-thermal problem is developed. The usefulness of the proposed system is verified by comparison of the obtained results with previously obtained ones with 3D simulation system. The developed system provides highly accurate results with much less computational effort and cost. In future, using the proposed system, we would like to further investigate and optimized the position of the additional induction heating sub-coils especially around the billet's low temperature zone.

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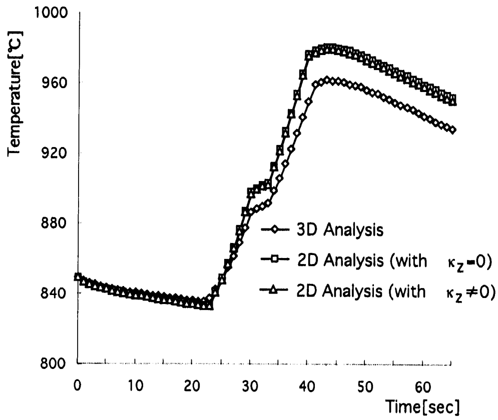

Fig. 9: Temperature record at point 3.

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