3-D Eddy Current Analysis of Induction Heating Apparatus Considering Heat Emission, Heat Conduction, and Temperature Dependence of Magnetic Characteristics

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The main issue of a billet heater using induction heating is to avoid billets that were not heated at a desired temperature. In order to improve the induction heating system, it is necessary to clarify the heating property of an object due to eddy current loss and to investigate the temperature distribution in an object by the magneto–thermal coupled analysis. In this paper, the eddy current and temperature distribution of a billet heater is analyzed considering the heat emission, heat conduction, and temperature dependence of magnetic characteristics of the billet. It is shown that the calculated values of temperature in the center and surface of a billet are in good agreement with measured values. The precise analysis is possible by considering the temperature dependence of magnetic characteristics, heat conductivity, etc. The detailed behavior of the heat generation in the billet is clarified. The skin depth is increased because the resistivity of the billet is increased and the permeability is decreased at high temperature. As a result, the flux in the billet is reduced, and then the power (eddy current loss) in the billet is decreased.

***Index Terms*—Finite element method, induction heating, magneto–thermal coupled analysis, temperature dependence of magnetic characteristics.**

I. Introduction

In a billet heater, a billet is heated by an induction heating system after it is cut to a constant length [1]. Then the billet is forged at a forging line. If the forging line is stopped, the operation of the billet heater is switched to the keeping-warm status, and then transported to the normal operation after the reoperation of the line. During such a standby operation, a suitable control of the billet heater is strongly required. In order to control the billet heater accurately so that the input and output of heat is well controlled, and to avoid billets that were not heated at a desired temperature, it is necessary to clarify the heating properties of billets by the magneto–thermal coupled analysis. But, the practical analysis of induction heating apparatus considering the temperature-dependent magnetic characteristics is little[2].

In this paper, the detailed behavior of the eddy current loss and the temperature distribution in billets are analyzed by the magneto–thermal coupled method considering the heat emission, the heat conduction, and the temperature dependence of magnetic characteristics of the billet. In addition, experimental results and analytical results are compared to examine the validity of the simulation.

II. Method for Analyzing 3-D Thermal Problem

The governing equation of 3-D transient heat conduction problem is as follows:

$$\frac{\partial}{\partial x}\left(\lambda_{xx}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{yy}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_{zz}\frac{\partial T}{\partial z}\right)+Q=\rho c\frac{\partial T}{\partial t} \quad (1)$$

where T is the temperature of the billet, λ is the thermal conductivity, Q is the rate of internal heat generation, ρ is the material density, c is the specific heat, and t is the time.

The boundary condition of the heat conduction is shown by the following:

$$\begin{aligned} q &= -[\lambda]\frac{\partial T}{\partial \boldsymbol{n}} = -[\lambda](\boldsymbol{n}\cdot\nabla T) \\ &= -\begin{bmatrix}\lambda_{xx} & 0 & 0\\ 0 & \lambda_{yy} & 0\\ 0 & 0 & \lambda_{zz}\end{bmatrix}\begin{bmatrix}\frac{\partial T}{\partial x}n_x\\ \frac{\partial T}{\partial x}n_y\\ \frac{\partial T}{\partial x}n_z\end{bmatrix} \end{aligned} \quad (2)$$

where q is the heat flow and $\boldsymbol{n}$ is the outgoing normal vector on the boundary.

The governing equation of heat conduction is discretized using 3-D nodal elements. The Galerkin equation is given by

$$\begin{aligned} &\iint_S q\{N\}^{\mathrm{T}}dS \\ &+\iiint_V\left\{\frac{\partial\{N\}}{\partial x}\left(\lambda_{xx}\frac{\partial\{N\}^{\mathrm{T}}}{\partial x}\right)+\frac{\partial\{N\}}{\partial y}\left(\lambda_{yy}\frac{\partial\{N\}^{\mathrm{T}}}{\partial y}\right)\right. \\ &\left.+\frac{\partial\{N\}}{\partial z}\left(\lambda_{zz}\frac{\partial\{N\}^{\mathrm{T}}}{\partial z}\right)\right\}dV\{T\}_e-\iiint_V Q\{N\}dV \\ &+\iiint_V \rho c\{N\}\{N\}^{\mathrm{T}}dV\frac{\partial\{T\}_e}{\partial t}=0 \end{aligned} \quad (3)$$

where $\{N\}$ is the interpolation function.

The equation of heat emission on the boundary is given by

$$\begin{aligned} q &= h(T-T_{\mathrm{out}}) \\ h &= \varepsilon\sigma F^*(T+T_{\mathrm{out}})\left(T^2+T_{\mathrm{out}}^2\right) \end{aligned} \quad (4)$$

where ε is the thermal emissivity, σ is the Stefan–Boltzmann coefficient, F^* is the radiation configuration factor, T_{out} is the temperature of ambient environment, and h is the coefficient of heat emission.

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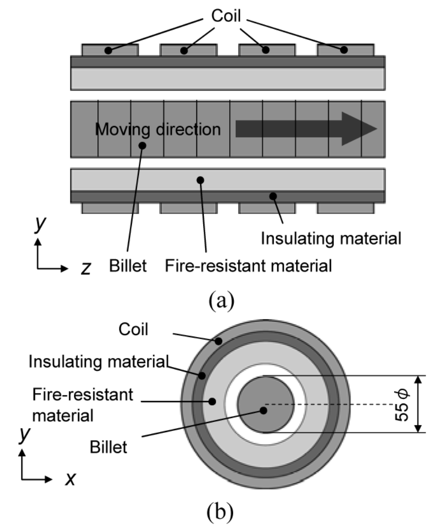

Fig. 1. Billet heater: (a) z–y plane, (b) x–y plane.

The finite element (FE) equation of the heat conduction problem that includes the heat emission is given by

$$[K]\{T\} + \{C\}\left\{\frac{\partial T}{\partial t}\right\} = \{F\} \tag{5}$$

where $[K]$ is the heat conduction matrix, $[C]$ is the heat capacity matrix, and $\{F\}$ is the heat flux vector. These are given by

$$\begin{aligned}[K] = &\iiint_V \left\{ \frac{\partial\{N\}}{\partial x}\left(\lambda_{xx}\frac{\partial\{N\}^{\mathrm{T}}}{\partial x}\right) + \frac{\partial\{N\}}{\partial y}\left(\lambda_{yy}\frac{\partial\{N\}^{\mathrm{T}}}{\partial y}\right)\right. \\ &\left. + \frac{\partial\{N\}}{\partial z}\left(\lambda_{zz}\frac{\partial\{N\}^{\mathrm{T}}}{\partial z}\right)\right\} dV \\ &+ \iint_S h\{N\}\{N\}^{\mathrm{T}} dS \end{aligned} \tag{6}$$

$$[C] = \iiint_V \rho c\{N\}\{N\}^{\mathrm{T}} dV \tag{7}$$

$$\{F\} = \iiint_V Q\{N\}^{\mathrm{T}} dV + \iint_S hT_{ou\tau}\{N\}^{\mathrm{T}} dS. \tag{8}$$

III. Magneto–Thermal Coupled Analysis Method

A. Analyzed Model and Analysis Condition

Fig. 1 shows the examined billet heater. The material of the billet is S45C (carbon steel). The insulating material is rolled out of the fire-resistant material. The Curie temperature of the billet is 760 °C. We assumed that the model is isotropic ($\lambda_{xx} = \lambda_{yy} = \lambda_{zz}$).

The 3-D FEM using edge elements is used for the magnetic field analysis, and 3-D FEM using nodal elements is used for the thermal field analysis. Although coils are divided into parts in an actual billet heater as shown in Fig. 1, it is assumed that they are not divided into parts in the analysis in order to make the analysis simple as shown in Fig. 2. Fig. 3 shows the cross section of the examined model. We considered the division of coils by feeding the current at the instant when the analyzed region corresponds to the cross section with the coil or by feeding no current at the instant when it corresponds to that without the coil.

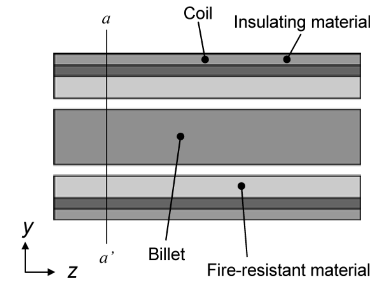

Fig. 2. Assumed model that is uniform in the z-direction.

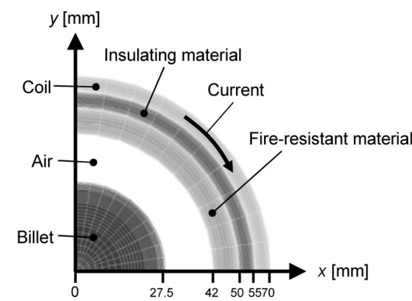

Fig. 3. Analyzed model (1/4 model).

The initial temperature of each material is 25 °C. The boundaries of analyzed region in Fig. 3 are assumed as the adiabatic boundaries.

B. Coupling of Magnetic and Thermal Analyses

The magneto–thermal coupled analysis considering the heat emission, heat conduction, and temperature dependence of magnetic characteristics of the billet is carried out according to the following procedures.

As a first step, the magnetic field and eddy current are analyzed using 3-D FEM. The basic equation is given by

$$\mathrm{rot}(\nu\ \mathrm{rot}\ \boldsymbol{A}) = J_0 - \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \mathrm{grad}\ \phi\right) \tag{9}$$

where $\boldsymbol{A}$ is the magnetic vector potential, ϕ is the electric scalar potential, σ is the conductivity, ν is the reluctivity, and J_0 is the current density of coil.

Next, the thermal analysis given by (5) is carried out. The eddy current loss obtained by the magnetic field analysis is used as the heat source.

The magnetic field analysis is carried out again by using the renewed material constants corresponding to the obtained temperature. Repeating these two kinds of analyses, the change of the temperature distribution in the billet with time is calculated. The time interval in the thermal analysis is chosen as one second.

C. Temperature Dependence of Material Properties

The material constants of the billet, air, fire-resistant material, and insulating material at 25 °C is shown in Table I. Figs. 4–7 show the temperature dependence of material constants of the

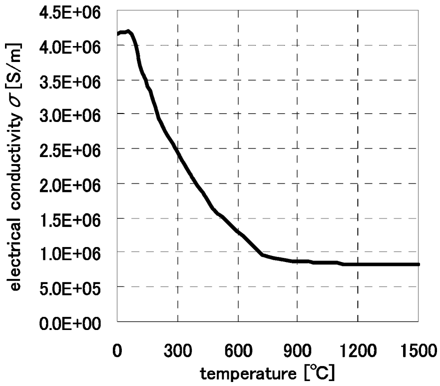

Fig. 4. Temperature dependence of electrical conductivity of billet.

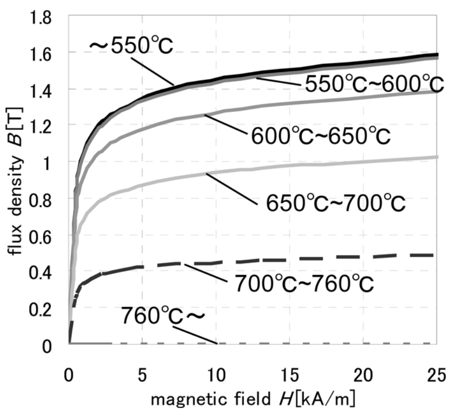

Fig. 5. Temperature dependence of B-H curve of billet (reference).

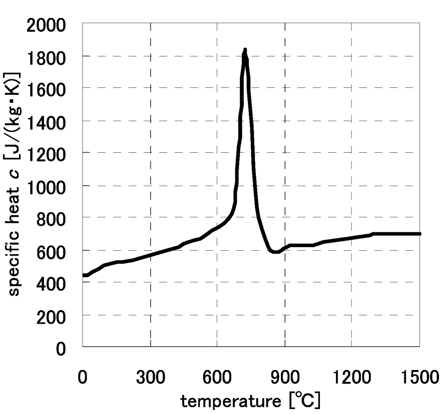

Fig. 6. Temperature dependence of specific heat of billet.

billet. The B-H curves are guessed from the B-H curve at 25 °C. In the analysis, these curves are linearly interpolated. As the purpose of the analysis is to examine the time change of the temperature distribution in the billet, the temperature dependences of fire-resistant material, insulating material, and air are neglected. The radiation configuration factors F^* of the billet and fire-resistant material of (4) are both assumed as unity.

IV. Results and Discussion

Fig. 8 shows the change of temperature at the center (r = 0 mm) and on the surface of billet (r = 27.5 mm) with time.

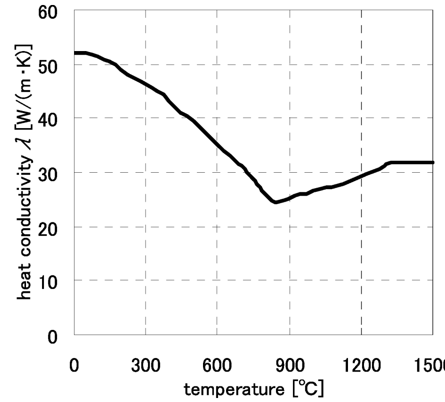

Fig. 7. Temperature dependence of thermal conductivity of billet.

TABLE I
Material Constants at 25 °C

Material	σ [S/m]	c [J/(kg・K)]	λ [W/(m・K)]	ρ [kg/m^3]	ε
Billet (S45C)	4.17×10^6	444.1	51.9	7860	0.85
Fire-resistant	-	1360	2.5	3160	0.7
Insulating material	-	1360	0.110	160	-
air	-	1005	002	230	-

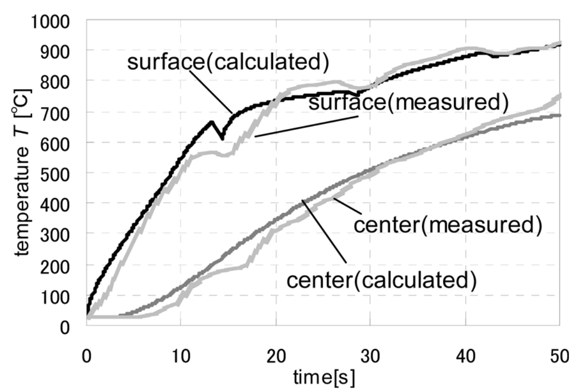

Fig. 8. Change of the temperature at the center and on the surface of the billet with time.

The temperature is measured using thermocouples. The calculated results are in good agreement with the measured ones. The reason why the rate of increase of temperature is reduced at around 20 s is that the temperature of the billet reaches near the Curie temperature at this instant, and the specific heat rises rapidly.

Fig. 9 shows the distribution of power (eddy current loss) and temperature in the billet. The power invades inside the billet with the increase of temperature, and its value is reduced. The reason is as follows: the skin depth is increased due to the decreased of the conductivity, and the flux is also decreased due to the decrease of the permeability at such high temperature. As a result, the generated eddy current loss (power) is decreased.

Figs. 10 and 11 show the changes of flux density and power in the billet with time. Fig. 10 shows that the flux is invaded inside the billet and its amplitude is decreased with time. Then,

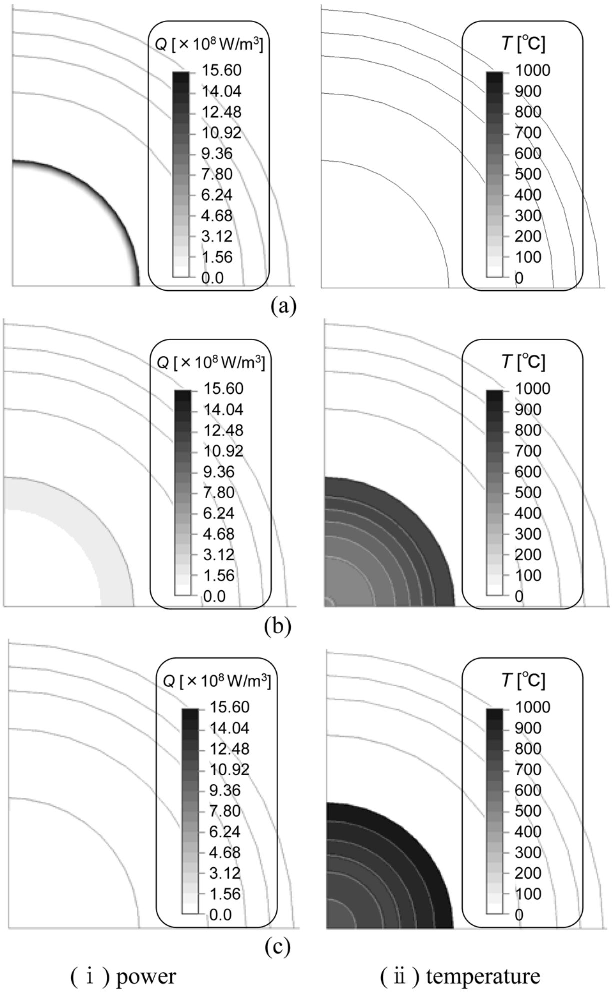

Fig. 9. Distribution of power and temperature in the billet: (a) 0 s, (b) 30 s, (c) 50 s, (i) power, (ii) temperature.

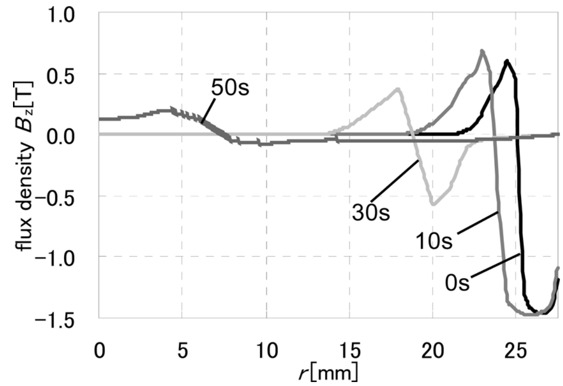

Fig. 10. Change of flux density in the billet with time.

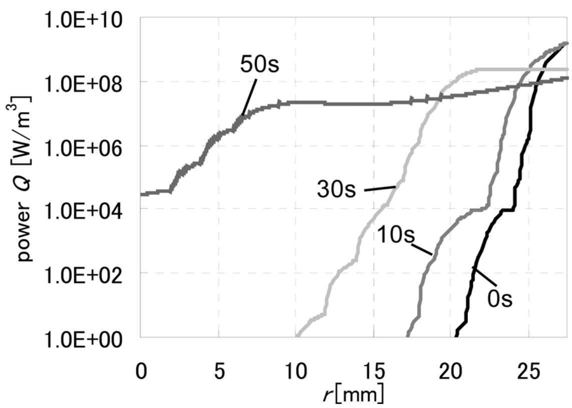

Fig. 11. Change of power in the billet with time.

the generation of power moves inside of the billet and its value is decreased as shown in Fig. 11.

V. Conclusion

The obtained results can be summarized as follows.

1) The precise analysis of power and temperature distribution in the billet is possible by considering the temperature dependence of magnetic characteristics, heat conductivity, etc.
2) The detailed behavior of the heat generation in the billet is clarified. The skin depth is increased because the resistivity of the billet is increased and the permeability is decreased at a high temperature. As a result, the flux in the billet is reduced, and then the power (eddy current loss) in the billet is decreased.

The detailed phenomenon of heat generation will give a useful suggestion for the improvement of the design and the operation of an actual billet heater.

References

[1] V. Čingoski, A. Namera, K. Kaneda, and H. Yamashita:, "Analysis of magneto-thermal coupled problem involving moving eddy-current conductors," *IEEE Trans. Magn.*, vol. 32, no. 3, pp. 1042–1045, 1996.
[2] I. R. Ciric, F. I. Hantila, and M. Maricaru:, "Novel solution to eddy-current heating of ferromagnetic bodies with nonlinear B-H characteristic dependent on temperature," in *Dig. Compumag Conf.*, 2007, no. PB7-10.
[3] W. H. Giedt, *Principles of Engineering Heat Transfer*. New York: Van Nostrand, 1957.