Effect of Temperature Dependence of Magnetic Properties on Heating Characteristics of Induction Heater

Hiroyuki Kagimoto[1], Daisuke Miyagi[1], Norio Takahashi[1], *Fellow, IEEE*, Naoki Uchida[2], and Keiji Kawanaka[2]

[1]Department of Electrical and Electronic Engineering, Okayama University, Okayama 700-8530, Japan
[2]Mitsui Engineering and Shipbuilding Company, Ltd., Tamano, Okayama 706-0014, Japan

In order to improve the induction heating system for an object of magnetic material, it is necessary to clarify the heating property of the object due to the eddy current loss using a magneto-thermal coupled analysis taking account of the temperature dependence of magnetic properties of a magnetic material to be heated. In this paper, the effect of temperature dependence of magnetic properties on heating characteristics of a billet heater is analyzed considering the heat emission, heat conduction and temperature dependence of magnetic properties of the billet. It is clarified that the precise analysis is possible by considering the temperature dependence of the magnetic property and the conductivity of a billet, heat emission, heat conduction etc. Moreover, the effect of temperature dependence of B-H curves on the temperature rise of a billet and the induced voltage of an exciting coil is examined.

***Index Terms*—Induction heating, magneto-thermal coupled analysis, temperature dependence of magnetic properties.**

I. Introduction

In order to well control the billet heater which is used, for example, for the shaft of car, it is necessary to clarify the heating properties of a billet made of magnetic material up to a defined temperature, for example about 1200°C, by the magneto-thermal coupled analysis. There are several papers about the eddy current and temperature analysis of induction heaters, but those are for heaters of non-magnetic materials [1], [2], heating higher than the Curie temperature (relative permeability is unity) [3], [4], analysis using a simple model of saturation magnetization as a function of temperature [5] or the temperature dependence of B-H curves is ignored [6]–[8]. Although the heating characteristics of the billet made of magnetic material, during the heating from the room temperature to more than 1000°C are affected by the temperature dependence of magnetic properties, the report of the precise discussion is few [9], [10]. One of the reason of the barrier for the precise analysis is the difficulty of measuring magnetic properties at high temperature [11].

In this paper, the necessity of the consideration of temperature dependence of B-H curves in the magneto-thermal analysis of billet heater is examined. The calculated temperature is compared with a measured temperature at the surface and the center of a billet in order to verify the validity of the simulation. Moreover, the effect of temperature dependence of the B-H curves on the temperature rise of a billet and the induced voltage of an exciting coil is examined using our simulation.

II. Model and Method of Analysis

A. Analyzed Model and Analysis Condition

Fig. 1 shows the examined billet heater. The material of the billet is S45C (carbon steel, carbon: 0.45%). The fire-resistant material is used as an insulating material. The Curie temperature of the billet is 760°C. We assumed that the model is isotropic.

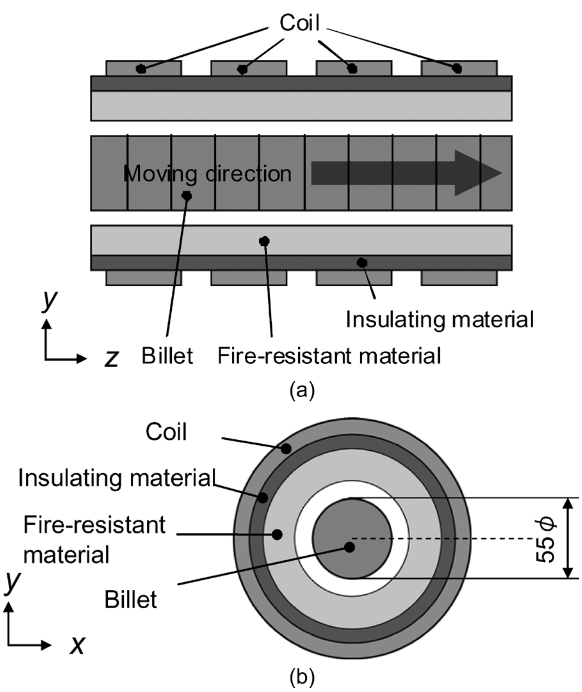

Fig. 1. Billet heater. (a) $z-y$ plane (b) $x-y$ plane.

The finite element method (FEM) using edge elements is used for the magnetic field analysis, and FEM using nodal elements is used for the thermal field analysis [9]. Although the exciting coil is divided into parts in an actual billet heater as shown in Fig. 1, it is assumed that the coil is not divided into parts in the analysis in order to make the analysis simple. Fig. 2 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 the cross section without the coil.

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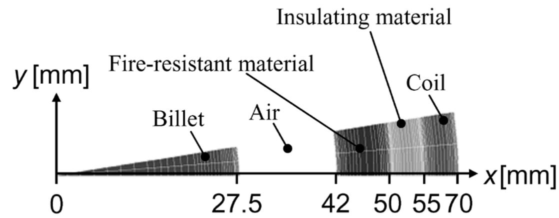

Fig. 2. Analyzed model (1/40 model).

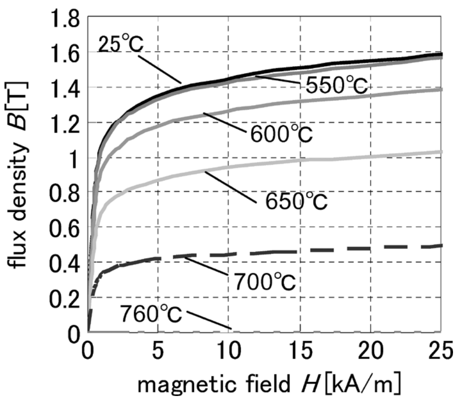

Fig. 3. Temperature dependence of B-H curve of billet (reference).

The initial temperature of each material is 25°C. The boundaries of the analyzed region in Fig. 2 are assumed as the adiabatic boundaries.

The temperature dependant magnetic properties of S45C are measured [11] up to 800°C which is higher than the Curie temperature, and the analysis is carried out using the measured B-H curves at different temperatures. Fig. 3 shows the reference value of the temperature change of the magnetic properties of the carbon steel. Actually, we used the interpolated curve using measured B-H curves at adjacent temperatures.

B. Coupling of Magnetic and Thermal Analyses

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

As a first step, the magnetic field and eddy current are analyzed using FEM. Secondly, the thermal analysis is carried out. The eddy current loss obtained by the magnetic field analysis is used as the heat source. Next, the magnetic field analysis is carried out again by using the renewed material constants corresponding to the obtained temperature. By repeating these two kinds of analyses at each time step, the change of the temperature distribution in the billet with time is calculated [9]. The time interval in the thermal analysis is chosen as 0.1 second for the whole analysis.

III. Results and Discussion

A. Comparison Between Measured Results and Calculated Results

In order to verify the importance of considering the heat emission and the temperature dependence of material constants of a billet in the magneto-thermal coupled simulation, the temperature change in a billet is analyzed by the magneto-thermal coupled method considering the heat emission and the temperature dependence of magnetic properties, the electrical conductivity, the specific heat and the thermal conductivity of a billet.

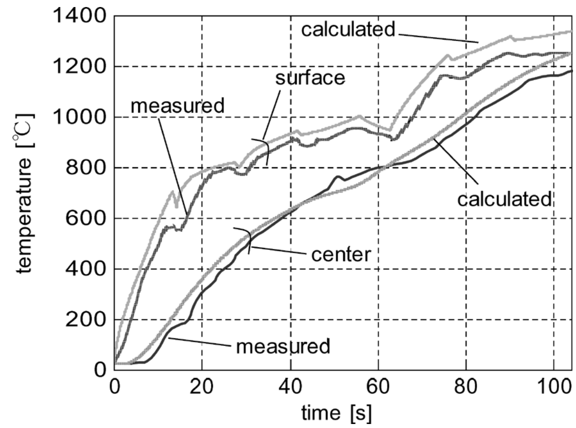

Fig. 4. Change of temperature at the center and surface of billet with time (comparison between measured value and calculated value).

Fig. 4 shows the comparison between measured results and calculated results which indicates the temperature change with time at the center $(r = 0\ \mathrm{mm})$ and the surface $(r = 27.5\ \mathrm{mm})$ of the billet. The temperature is measured using thermo-couples. The calculated results are in good agreement with the measured ones at both the center and the surface of a billet. The result shows that the precise analysis of the heating process by the induction heating is possible by considering the temperature dependence of the magnetic properties, the electrical conductivity, the specific heat and the thermal conductivity of an object to be heated.

B. Effect of Temperature Dependence of Magnetic Properties on Accuracy of Analysis

Fig. 5 shows the comparison of the calculated results of the temperature in a billet when the temperature dependence of magnetic properties is considered (case A) and that when it is not considered (case B). In the case when the temperature dependence is not considered (case B), the B-H curve at 25°C is used from the room temperature to the Curie temperature, and the permeability of the vacuum is used above Curie temperature. As shown in Fig. 5, the calculated temperature without consideration of the temperature dependence of the magnetic properties (case B) is higher than that considering the temperature dependence of the magnetic properties (case A). After the heating of the billet of about 15 seconds, the temperature reaches at nearly the Curie temperature, the temperature difference becomes the maximum. The temperature difference is about 80°C (10%) at 15 seconds, and that at 100 seconds is about 35°C (3%). The reason for such a property can be discussed considering the distribution of flux and power in the billet as follows:

Figs. 6 and 7 show the changes of flux density and power (eddy current loss) in the billet with time. Fig. 6 shows that the maximum value of the flux density is quickly decreased when the temperature is increased. This is, because the permeability at

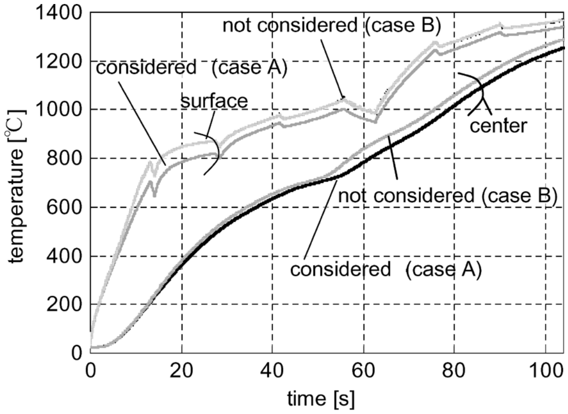

Fig. 5. Change of temperature at the center and surface of billet with time.

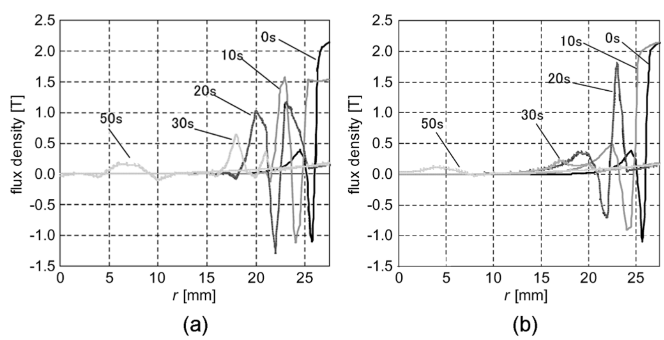

Fig. 6. Change of flux density in the billet with time. (a) temperature dependence of magnetic properties is considered (case A) (b) it is not considered (case B).

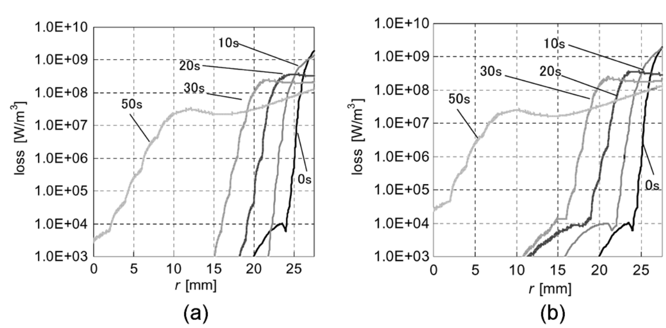

Fig. 7. Change of power in the billet with time. (a) temperature dependence of magnetic properties is considered (case A) (b) it is not considered (case B).

an operating flux density (not initial permeability) is decreased with the increase of temperature in the case A. On the contrary, the maximum value of the flux density is not so much decreased in the case B. This is, because the permeability is not changed until the Curie temperature in the case B. The power in the case B is lager than that in the case A, as the flux density in the case B is larger than that in the case A. Therefore, the temperature in the case B, when the temperature dependence is not considered, is higher than that in the case A when it is considered.

Fig. 8 shows the maximum values of the induced voltage of the exciting coil at every cycle. In both cases A and B, the voltages of exciting coil reach the maximum values just before the instant when the temperature at the surface of the billet reaches the Curie temperature. If the temperature dependence is ignored

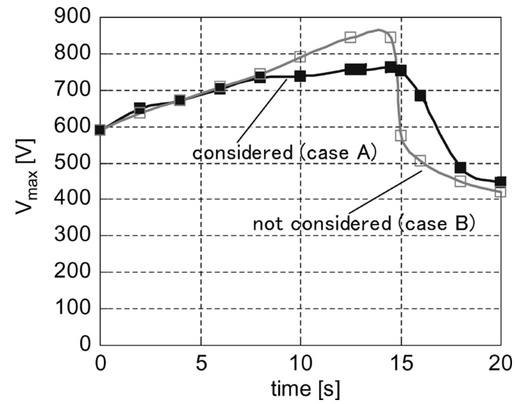

Fig. 8. Change of maximum value of induced voltage with time.

(case B), the calculated voltage is about 100 V higher than the actual value in this case. This is, because the flux in the case B is larger than that in the case A.

The reason why the voltage begins to increase at about 15 seconds is that the temperature near the surface exceeds the Curie temperature at this instant. Therefore, it is very important to calculate the maximum value of the exciting coil voltage using the magneto-thermal coupled method considering the temperature dependence of the magnetic properties for the design of the inverter capacity.

IV. Conclusion

The obtained results can be summarized as follows:

1) The precise analysis of eddy current loss and temperature distribution in a billet and the voltage of exciting coil is possible by considering the temperature dependence of the magnetic properties, the heat emission, the electrical conductivity, the specific heat and the heat conductivity. If the temperature dependence of magnetic properties is not taken into account, the calculated temperature becomes about 80°C higher in the model examined in this paper.
2) The induced voltage of the exciting coil reaches the maximum value just before the instant when the temperature at the surface of the billet reaches the Curie temperature. If the temperature dependence is ignored, the calculated voltage exceeds about 100 V in the examined model. Therefore, the consideration of the temperature dependence is indispensable for the design of inverter capacity.

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