Thermal Analysis of Induction Heating Roll With Heat Pipes

Seok-Myeong Jang, *Member, IEEE*, Sung Kook Cho, Sung-Ho Lee, Han Wook Cho, and Hee Chang Park

***Abstract*—This paper deals with temperature performance of induction heating roll with or without heat pipes. The focus of this paper is to improve nonuniformity of the outer surface temperature of the roll by inserting heat pipes with very high thermal conductivity. In our work, the coupled magneto-thermal finite-element analysis considering skin effect is employed for evaluating the surface temperature. The predicted results are verified with experimental data.**

***Index Terms*—Coupled magneto-thermal finite-element analysis (FEA), heat pipe, induction heating, temperature performance.**

I. Introduction

THE HEATING roll is heated by circulating oil or inserting a cartridge heater inside the cylindrical roll. Recently, induction heating roll, which uses eddy current loss for generating heat in the roll, is generally used. The nonuniformity of temperature distribution on the outer roll surface of such a device results in the local hot spots and causes deterioration of raw material.

Heat pipe is becoming more widespread as heat pipe costs fall and is being applied in the electronics industry. It also helps the temperature distribution to be divided equally on the cylindrical roll surface [1].

This paper deals with thermal performance of induction heating roll with or without heat pipes in order to improve nonuniformity of the outer roll surface temperature. For calculating the temperature distributions of the heating roll, the coupled magneto-thermal finite element analysis is employed. In our work, eddy current and its loss density considering nonuniformity along the axial position and the skin effect in the roll was investigated first. The evaluated eddy current loss density is substituted for heat source in the heat transient transfer equation. Then, the effect of length, number, and diameter of heat pipe on the temperature distribution of the outer roll surface is reviewed. The numerical results are compared to experimental data for the manufactured heating roll with heat pipes.

II. Method of Analysis

A. Induction Heating Roll

Fig. 1 shows the structure of induction heating roll with heat pipes in the steel roll. The device is composed of laminated silicon core, bobbin, steel-roll, induction coil, and heat pipes inserted with the same interval in the roll. The induction coils are positioned close to the inner face of the cylindrical roll. The induction coils are driven by time-varying current with frequency of 60 Hz.

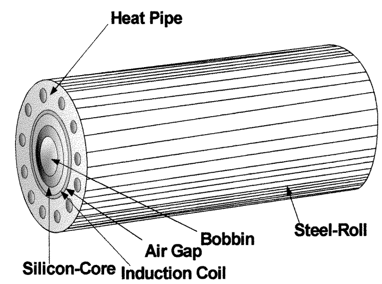

Fig. 1. Schematic of the induction heating roll with heat pipes.

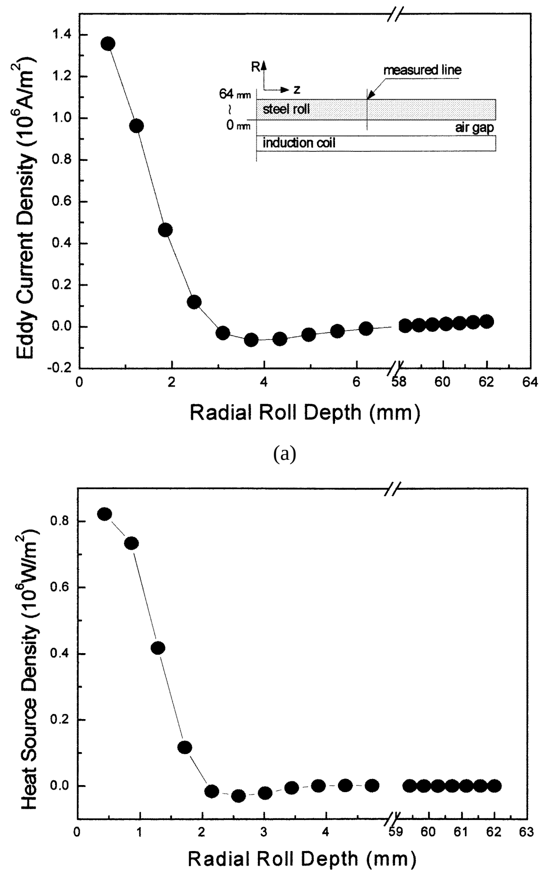

Fig. 2. (a) Eddy current density according to radial roll depth. (b) Heat source density according to radial roll depth.

Manuscript received January 6, 2003.

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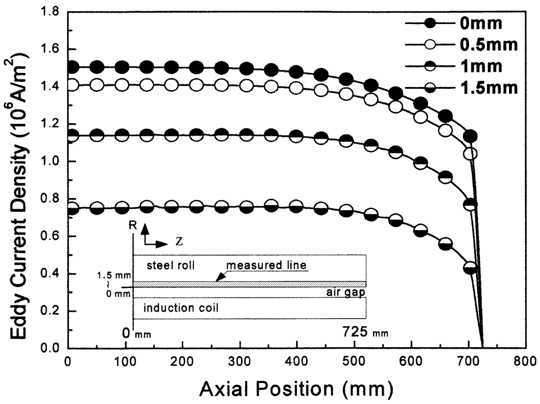
Digital Object Identifier 10.1109/TMAG.2003.816735



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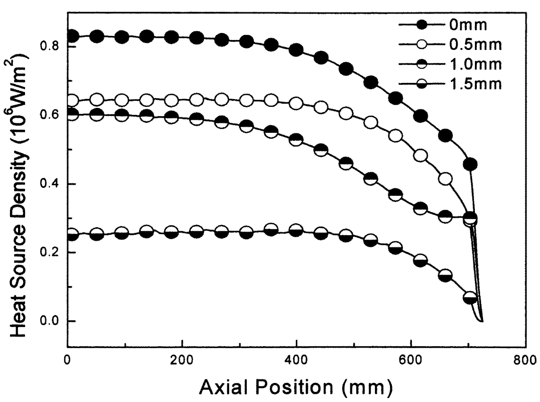


(b)

Fig. 3. (a) Eddy current. (b) Heat source density according to the axial position on the roll surface.

B. Electromagnetic Field Analysis

The governing equation about steady-state eddy current problem is given by

$$\frac{1}{\mu}\nabla^2 A = J_e + j\sigma\omega A \tag{1}$$

where J_e is the excitation current source, μ is magnetic permeability, $\boldsymbol{A}$ is the magnetic vector potential, ω is the angular velocity of the current source, and σ is the electric conductivity. The system matrix can be written as [2]

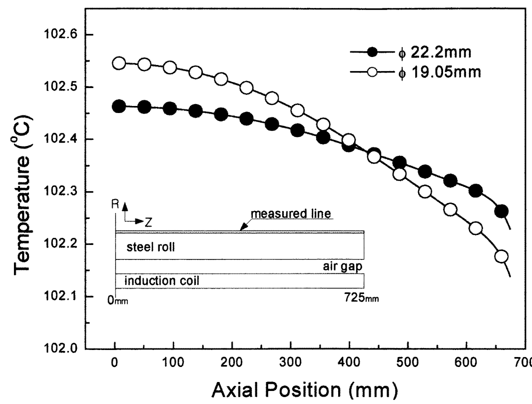
$$[\{P\} + j\{Q\}]\{A\} = \{S\}. \tag{2}$$

The eddy current density induced in the roll by the time-varying magnetic field is given by

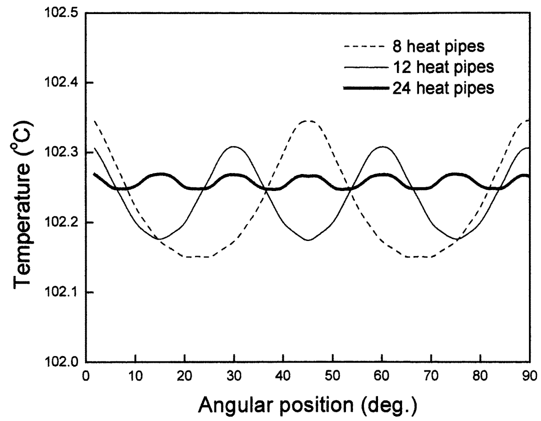
$$J_e = \sigma E = -j\omega\sigma A. \tag{3}$$

The Joule loss due to the eddy current is substituted for the heat source density. Heat source density is expressed as

$$q = \frac{1}{\sigma}\left(\mathrm{Re}(J_e)\right)^2. \tag{4}$$



(a)



(b)

Fig. 4. (a) Comparison of the effect of heat pipe diameter on the surface temperature distribution according to axial position. (b) Comparison of the effect of the heat pipe number on the surface temperature distribution according to angular position.

C. Thermal Field Analysis

In the thermal problem, the heat-transient transfer equation is represented as

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-K\nabla T) = q \tag{5}$$

where ρ is the mass density, C_p is the specific heat, K is the thermal conductivity, and q is the heat source density by the eddy current. Equation (5) can be solved with the following boundary conditions at the surface of the roll [3], [4]:

$$-K\frac{\partial T}{\partial n} = h(T - T_a) + \lambda(T^4 - T_a^4) \tag{6}$$

where

- n unit normal to the boundary;
- h convection coefficients;
- λ radiation coefficients;
- T_a ambient temperature.

III. Results and Discussions

Fig. 2(a) and (b) shows the eddy current and the heat source density according to the radial roll depth, respectively. It can be seen that the eddy current and heat source density are concentrated on the inner roll surface due to the skin effect. Fig. 3(a)

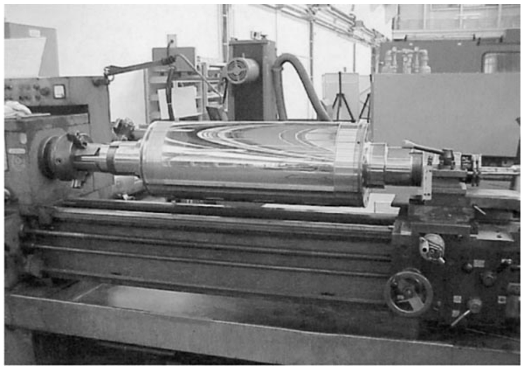


Fig. 5. Photograph of the manufactured induction roll with heat pipes.

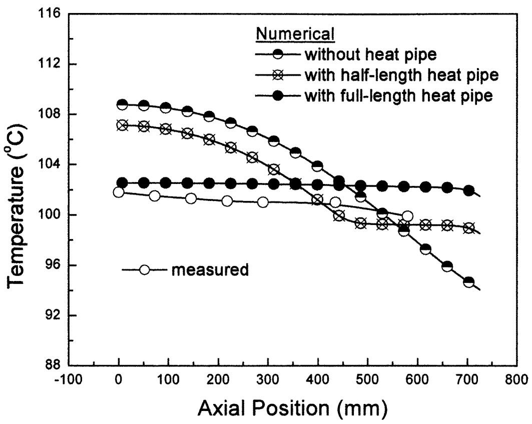


Fig. 6. Comparison of the effect of heat pipe length according to the axial position on the outer roll-surface temperature. Plots also compare numerical results with the measured data.

and (b) shows the effect of leakage flux on the eddy current and the heat source density according to the axial position in the inner roll surface, respectively. It can be observed that eddy current and heat source density distributions due to the effect of leakage flux decrease as the axial position goes the edge. The temperature distributions on the outer roll surface are calculated from (5). In (6), the conductivity K of mild steel is 45 W/mK, the convection coefficient h is 10 W/m^{2}K, and the radiation coefficient λ around the roll surface is 4.82 W/m^2/K^4.

Fig. 4(a) compares the effect of heat pipe diameter on the surface-temperature distribution according to axial position for the heating roll with 12 heat pipes. It can be seen that induction heating roll with each heat pipe diameter, $\phi 19.05$ mm and $\phi 22.2$ mm, has the surface temperature variation of 0.35 °C and 0.2 °C between the center and the edge of the roll, respectively. Fig. 4(b) shows the effect of heat pipe number on the temperature distribution according to angular position. It can be observed that temperature variation for the induction heating roll with 24 heat pipes has the best uniform temperature distribution. In this case, the temperature variation is within 0.05 °C.

Fig. 5 shows the manufactured model of induction heating roll with 12 heat pipes. Table I shows the specifications of the manufactured device. Fig. 6 compares the effect of heat pipe length on the roll surface temperature according to axial position. The temperature variation of the induction heating roll without heat pipes is about 14 °C between the center and edge of the roll. The temperature difference of the roll with half-length heat pipes is about 8 °C between maximum and minimum value. The temperature variation with full-length heat pipes is within 0.5 °C. Fig. 6 shows also the comparison of calculated values with experimental data for the manufactured device. The measurement is performed within 1 h after the switch on. The numerical results are within 5% error compared with the measured temperature variation.

TABLE I
SPECIFICATIONS OF THE INDUCTION HEATING ROLL WITH HEAT PIPE

Parameters	Values	(Unit)
Work Power	30	(kVA)
Coil Current	150	(A)
Coil Turns	147	(Turns)
Axial Length of the Roll	1450	(mm)
Single Phase Voltage	220	(V)
Frequency	60	(Hz)
Material of the Roll Cylinder	Mild Steel	
Heat Pipe Diameter	ϕ 22.2	(mm)
Heat Pipe Number	12	
Heat Pipe Length	725×2	(mm)

IV. CONCLUSION

In this paper, the application of heat pipe was presented to improve nonuniformity of induction heating roll. Two problems involving coupled electromagnetic and thermal field were calculated by using the finite element analysis. The eddy current density and heat source density distribution in the roll were investigated first. From the heat source density obtained by the magnetic field finite element analysis, temperature distribution on the roll surface considering the effect of length, number, and diameter of heat pipe has been investigated.

It was confirmed that the induction heating roll with heat pipe has more uniform temperature distribution than heating roll without heat pipe. From the comparison between numerical and experimental results, the effectiveness of heat pipe application on induction heating roll was presented.

ACKNOWLEDGMENT

This work was financially supported by MOCIE through the IERC program.

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