A Numerical Study of Induction Heating Fusers

Shogo Yokota, Toshiaki Kagawa, and Atsuyuki Katoh,
Sharp Corporation
Document Products Development Laboratories, Digital Document Systems Group
Yamatokoriyama, Nara, Japan

Abstract

The reduction of a power consumption by electro-photographic copiers and printers has become an important topic in recent years.

We are developing a new fuser with a highly efficient induction heater in order to reduce the power consumption of electro-photographic system. However, there is no effective method for designing an induction heating fuser, and it is necessary to repeat many experiments in order to determine the optimum conditions.

To reduce the number of experiments needed, we used the Finite Element Method (FEM) to perform heating simulations, and then compared the simulation results with the actual measured data to verify the simulation results.

The results of this comparison show that the induction heating conditions and temperature distribution of the heating roller can be precisely estimated by the heating simulation, making the heating simulation an effective method for use in the design of the induction heating fuser.

Introduction

In recent years, there has been a growing trend for the development and wide spread application of low-power electronic devices. Such devices are appearing more frequently because the reduced power consumption can contribute to the resolution of environmental problems.

Likewise, the development of low-power-consumption technologies in the field of office equipment, which includes copiers and printers, has also become a key issue. In particular, the fuser in copiers and printers, which melts the toner and fixes it to the paper, consumes a large amount of power. Therefore, one effective means of reducing power consumption is to develop a new fuser that requires less power for the fusing process. With this in mind, we have focused our attention on induction heating, which has excellent heating efficiency, and are studying the application of this method as a fuser heat source in order to reduce power consumption.

However, there was no effective method for designing an induction heating fuser (IH fuser), so it was necessary to repeat many experiments in order to determine the optimum heating conditions. As such, we conducted heating simulations using the Finite Element Method(FEM) and in order to determine whether this type of simulation could be used to reduce the number of experiments needed, we conducted comparative verifications with actual measured data. The results indicated that the simulation could predict heating conditions and temperature distributions with good accuracy, and that the simulation could be used to design fusers.

In this paper, we would like to report on the effectiveness of this method.

Induction Heating

Induction Heating Fuser Configuration and the Principle of Heat Generation

The configuration of the IH fuser is shown in illustrations a), and b) of Fig. 1. The layout and shape of the induction coil are shown in illustrations a), and b) is a cross section of the IH fuser when the induction coil is placed inside the roller.

As the diagram shows, the only distinguishing feature of the IH fuser is the use of an induction coil instead of a halogen lamp. In other respects, the basic configuration of the IH fuser is the same as that of conventional fusers. The induction coil is connected to an inverter circuit and is configured for a high-frequency current flow of 20 kHz or higher.

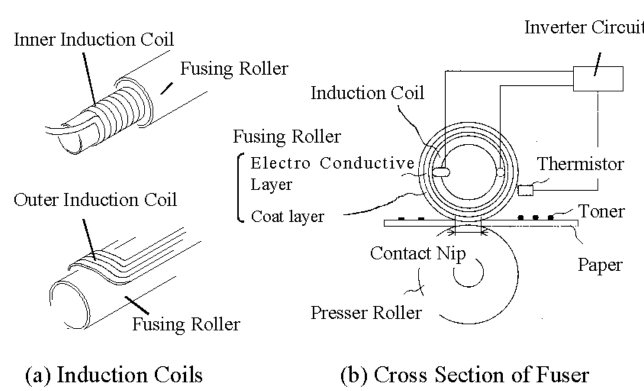


Figure 1. Schematic Diagram of an Induction Heating Fuser

Figure 2 shows the basic principle of induction heat generation. The board-shaped component is conductive, and corresponds to the fusing roller.

As shown in the diagram, the induction coil generates an alternating magnetic field around itself when an alternating current flows through the coil. The conductive component placed near the coil heats up due to Joule's heat from the eddy current that flows in opposition to changes in the magnetic field in the conductive component.

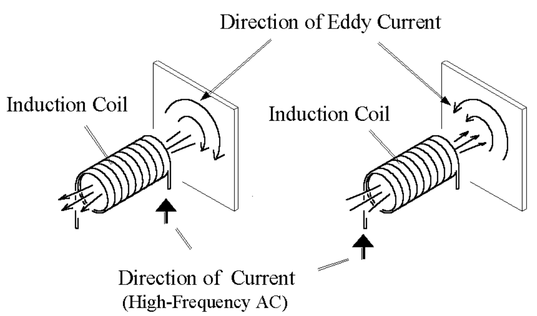


Figure 2. Eddy Current Generated by Induction Coil

Magnetic Matching of the Fusing Roller and Induction Coil

The amount of heat generated by the fusing roller in the IH fuser is strongly affected by the magnetic matching of the fusing roller and the induction coil. This magnetic matching is shown in the equivalent circuit in Fig. 3.

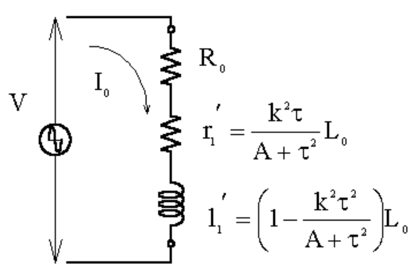


Fig. 3 Equivalent Circuit between the Induction Coil and Fusing Roller

The relationship between the coil current and the voltage is given by Equation (1).

$$V = \left(R_0 + \frac{k^2\tau}{A+\tau^2}L_0\right)\cdot I_0 + \left(1 - \frac{k^2\tau^2}{A+\tau^2}\right) j\omega L_0 \cdot I_0$$

where

$$\tau = \frac{L_1}{R_1}, \quad k = \frac{M}{\sqrt{L_0 L_1}}, \quad A = \frac{1}{\omega^2}$$

L_0: self-inductance of induction coil
L_1: self-inductance of fusing roller
R_0: resistance of induction coil
R_1: resistance of fusing roller
M: mutual inductance
ω :2 π f, f: frequency

From this equation, we can see that the induction coil must be designed for a high r_1' value in order to achieve highly efficient heating.

Fundamental Heating Simulation Concept

Equation (1) has many unknowns and cannot be solved. Furthermore, the distribution of heat generation cannot be predicted by the equation. Thus, the optimum heating conditions of the IH fuser must be obtained through experiments, however, there are a large number of control factors, so this is not an easy task.

In order to reduce the amount of work involved in testing, we performed an analysis of magnetic matching and heat generation distribution using FEM heating simulation.

In the following section, we explain the basic equations used in the heating simulation. These equations are the Maxwell's equations (2), and we solved them using the vector potential method (3).

$$\mathrm{rot}E = -\frac{\partial B}{\partial t}$$
$$\mathrm{rot}H = J + \frac{\partial D}{\partial t}$$
$$\mathrm{div}B = 0$$
$$\mathrm{div}D = \rho$$

E : electric field intensity
B : magnetic flux density
H : magnetic field
J : current density
D : electric flux density
ρ : electric charge density

Heating Simulation

Two-Dimensional Simulation

In order to select a suitable roller material and thickness, we began by performing heating simulations using a two-dimensional model.

Figure 4 shows the analytical model that we used in the simulations, and Table 1 shows the calculation conditions. We used the analytical model and calculation conditions to obtain the relationship between the roller material and the amount of heat generated. The results are shown in Fig. 5. The horizontal axis shows roller thickness, and the vertical axis shows the amount of heat generated. We can see from Fig. 5 that the maximum heat generated varies depending on the roller material, and that stainless steel materials result in higher heat generation than an iron.

Table 1. Calculation Conditions

Coil Current	20 A_{rms}
Frequency	20 kHz
Roller Material	Al, Fe, SUS304, SUS430

In order to confirm the results of our calculations, we conducted heating experiments using a tester (described later) and calculated the heat generation quantities. Table 2 shows the results of our tests, and these show the same trends as the simulations.

Because the heating simulations and the experiment results show the same trends, we concluded that the use of heating simulation to obtain test conditions is an effective means of reducing the number of tests that must be performed. In particular, the analytical model in a two-dimensional simulation is easy to create and analysis can be completed in a short time, thus making the two-dimensional simulation well suited for determining heating conditions.

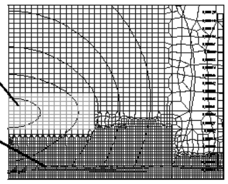


Figure 4. Analysis Model and the Distribution of Magnetic Flux Density

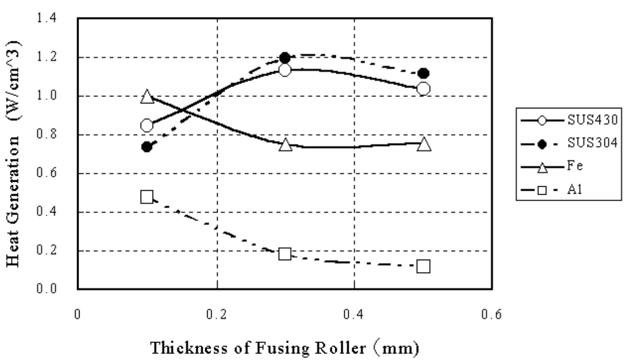


Figure 5. Heat Generation

Table 2. Heating Measured in the Experiment (for One Sample)

	Fe	SUS304
Heat generation (W/cm^3)	17.9	28.4

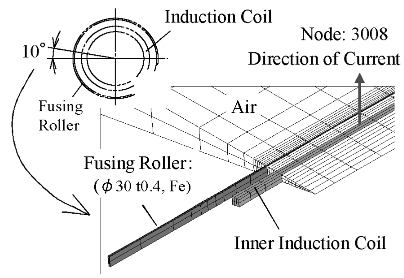
Three-Dimensional Heating Simulations

In order to determine the section of the fusing roller with uniform heat distribution, we obtained temperature distributions using three-dimensional heating simulations.

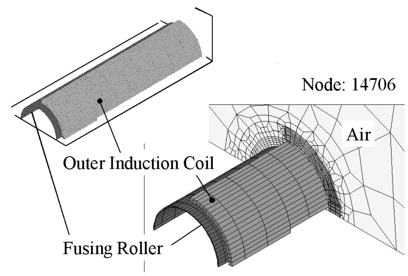
Three-dimensional heating simulations were performed with respect to two types of induction coils. The first type was placed inside the roller and the second type was placed outside the roller. The inner coil had a solenoid shape, and the outer coil was shaped to cover half of the circumference of the roller. The inductance values of both induction coils were selected to equal the inductance value of the coil used in our company's induction heating cookers.

The analytical models of the coils are shown in Fig. 6, illustrations a) and b). To reduce calculation nodes, a compact shape was selected for both, with the shape divided into "reference surfaces".

The results of the simulations are shown in Fig. 7, illustrations a) and b). Both induction coils show decreased heat generation at the ends.

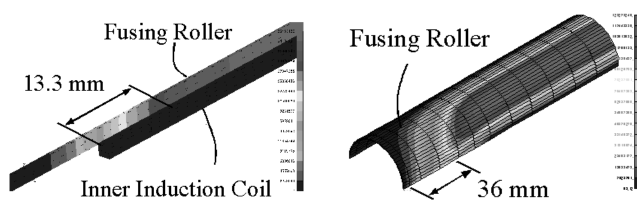


(a) Inner Induction Coil and Fusing Roller



(b) Outer Induction Coil and Fusing Roller

Figure 6. Analytical Models



(a) Inner Induction Coil *(b) Outer Induction Coil*

Figure 7. Heat Distribution of Heating Roller

Comparison of Simulation Results with Experiment Results

Testers Used in the Experiments

We measured temperature distribution using the IH fuser shown in Fig. 8. We used our company's quasi-resonant converter circuit for induction heating cookers for the inverter circuit that drives the induction coil.

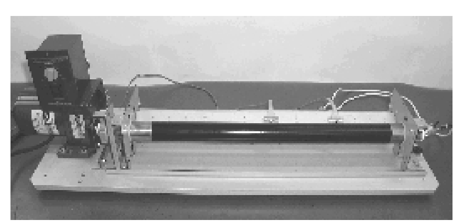


Figure 8. IH Fuser Used to Verify Simulation Results

Experimental Results (Heat Generation Distribution)

Figure 9 shows the heating test results for the induction coil placed inside the fusing roller. The top diagram shows the temperature distribution of the entire fusing roller, and the bottom diagram plots the temperature distribution of the center of the fusing roller along the roller axis.

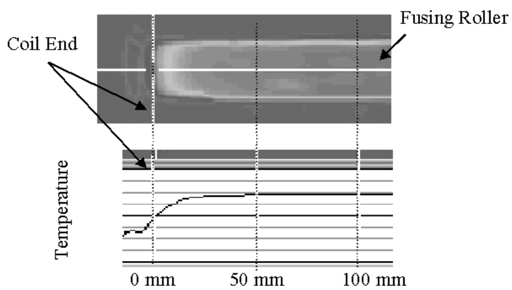


Figure 9. Temperature Distribution (Inner Coil)

The diagrams show a dramatic change in the temperature distribution of the fusing roller in an area 20 mm from the ends of the induction coil, and thus, the temperature distribution obtained from the experiment agrees well with the temperature distribution obtained from the heating simulation.

For the induction coil placed on the outside of the fusing roller, we first measured the temperature distribution with the fusing roller stopped and then with the fusing roller rotating, and compared the results with the simulation results.

To measure the temperature distribution with the fusing roller stopped, we used the measuring roller shown in Fig. 10, which was a cylinder cut in half. The results of the measurements are shown in Fig. 11.

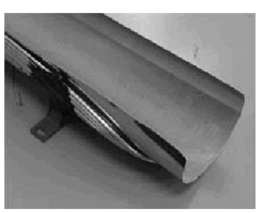


Figure 10. Cut Roller

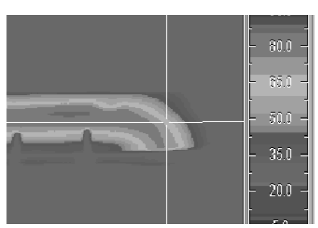


Figure 11. Temperature Distribution

As can be seen from the diagrams, the temperature distribution resembles the shape of the induction coil, and heat generation drops at the points where the coil bends back. This temperature distribution is the same as the temperature distribution obtained from the heating simulation.

The results of our temperature distribution measurements with the fusing roller rotating are shown in Fig. 12. The vertical axis indicates the temperature and the horizontal axis indicates the distance from the roller center. The heat generation distribution was obtained in the simulation by integrating the distribution in the circumferential direction. As can be seen from the diagrams, heat generation drops at the points where the coil bends back in both the simulation and the experiment, and the results of both are nearly the same.

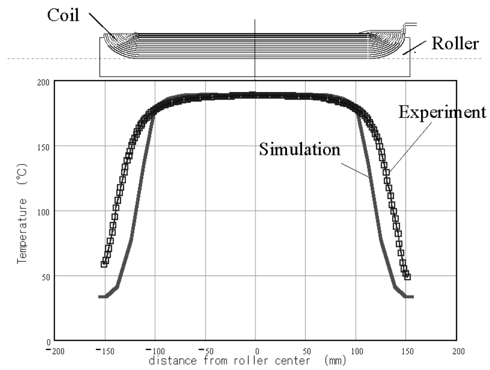


Figure 12. Temperature Distribution (Outer Coil)

IH Fuser Inductance

Figure 13 shows the relationship between inductance and frequency when the induction coil and fusing roller are magnetically coupled. The displayed data shows the values determined by the simulation and actual measured values for two types of fusing roller materials with different conductances and relative permeabilities. For reference, data is also included for an induction coil when no fusing roller is present. The vertical axis indicates the inductance and the horizontal axis indicates the frequency.

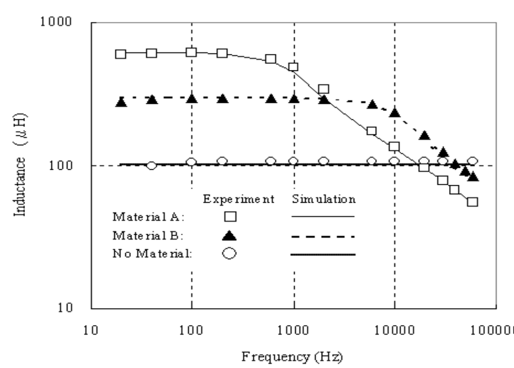


Figure 13. Relationship between Inductance and Frequency

One thing that should be noticed is that the inductance has an inflection point at a certain frequency, and is constant at frequencies below this inflection point. At frequencies above the inflection point, the inductance undergoes simple harmonic decrease as the frequency increases. This phenomenon is thought to be the result of a magnetic field being generated inside the fusing roller due to an eddy current that develops in the fusing roller, creating an apparent overall decrease in inductance.

We can also see from this figure that the higher the relative permeability of the material, the more the inductance increases on the low frequency side, and that the frequency at which the inductance begins to decrease increases with the resistance of the roller material.

As the inductance of the IH fuser obtained by this simulation agrees with the experiment results, this method is proven to be useful in the prediction of an inverter circuit's constant prior to testing.

Conclusions

The following is a summary of what we learned through our comparison of the results of the FEM heating simulation with the results from our experiment.

- The relationship between the fusing roller material and heat generation can be obtained by two-dimensional simulation, and the trend shown by the simulation results agrees closely with the experimental results.
- The temperature distribution obtained by the three-dimensional simulation agrees well with the experiment results, regardless of the inductive coil shape.
- The induction fuser inductance value obtained by this simulation agrees well with the experimental results, regardless of the frequency.

These results have indicated that this simulation provides an effective means for obtaining an optimum design for an IH fuser and for establishing testing conditions.

In the future, we would like to develop this heating simulation method further so that it can be used to analyze a heat generation efficiency, and we would also like to establish a system that can be used to design an IH fusers more efficiently. This report is part of the, "Development of Technology to Reduce Standby Power Consumption in Office Machines " collaborative research project of the NEDO (New Energy and Industrial Technology Development Organization, Japan).

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Biography

Shogo Yokota received a Master's degree in Mechanical Engineering from Tottori University in 1991, and joined Sharp Corp. Since then he has been engaged in the research and development of copiers and printers. His current work is the development of the fuser system. He is a member of the Japan Society of Mechanical Engineers.