Designing of Suitable Construction of High-Frequency Induction Heating Coil by Using Finite-Element Method

Alexander Boadi, Yuji Tsuchida, Takashi Todaka, and Masato Enokizono, *Member, IEEE*

Department of Electrical and Electronic Engineering, Faculty of Engineering, Oita University, Oita 870-1192, Japan

This paper describes the three-dimensional (3-D) modeling of an induction heating system. To realize the suitable construction of a high-frequency induction heating coil, numerical computations of eddy currents and heat conduction have been carried out by using the finite-element method (FEM) and also taking into account the dependence of material properties on temperature. For a high-frequency induction heating coil, which is normally applicable for heat treatment, the tubular solenoid design is the most appropriate due to its high coil efficiency. Coil efficiency is that part of energy delivered to the coil, which is transferred to the workpiece. Besides coil efficiency, the heating pattern and the production rate are also important. As the heating pattern reflects the coil geometry, optimal coil design is a prerequisite to attain the desired heating. Several modifications, such as spacing in between coil turns, the motion of the workpiece relative to the coil, and dimensional parameters, were carried out until optimal design was achieved.

***Index Terms*—Finite-element method (FEM), high-frequency, induction heating, optimized coil.**

I. INTRODUCTION

ONE typical example of magnetic-field/heat coupled analysis is demonstrated during induction heating. The basic components of an induction heating system are the alternating current supply, the induction coil, and material to be treated or heated, normally referred to as the workpiece. The power supply sends alternating currents through the coil, generating a magnetic field. When a workpiece is placed in the coil and enters the magnetic field, eddy currents are induced within the workpiece, thereby generating precise amounts of clean localized heat without contact between the coil and workpiece.

With regard to the fact that material properties change drastically with temperature variations during an induction heating process and the difficulty in combining magnetic field and thermal analyses, analytical methods are very difficult to implement. Therefore, a powerful computer-aided numerical tool, by using the finite-element method (FEM) is proposed to numerically model these coupled analyses [1]. This program has a high capability of handling various geometries and elements. Input and output techniques are exceptionally versatile and efficient.

In high-frequency induction heating, the induced current is usually not uniform throughout the workpiece. It is concentrated at the surface. However, the surface heat concentration can create unwanted results or waste. Overheating of locations such as the outside corner can result in quench cracking or inadequate ductility for the intended service. If the potential benefits are to be achieved, the induction tool must be designed carefully. Thus, a good coil design is needed, which normally depends on experience [2].

Most past researchers have engaged in two-dimensional (2-D) simulations, with regard to this topic, due to its simplicity. However, we have to perform three-dimensional (3-D) simulations, which are cumbersome and complicated but give a vivid view of how the heating is being effected in the workpiece, thereby giving us a better understanding and approach for its applications. Computer simulations by using FEM, for this project, were carried out to access the heating process of a nonmagnetic material, using original and proposed coils under a frequency of 60 kHz.

Digital Object Identifier 10.1109/TMAG.2005.854993

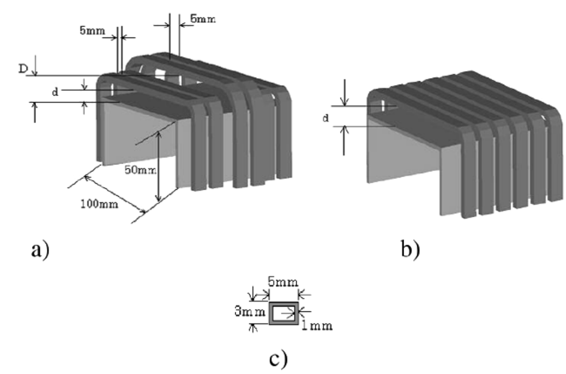

Fig. 1. Analysis model. (a) Proposed coil. (b) Original coil. (c) Tubular dimensions of coil.

II. CONFIGURATION OF MODEL

Fig. 1 shows the configuration of half of the model with the original and proposed coils, of the induction heating system, which comprises a cut rectangular tube workpiece, 3 mm in thickness, and a tubular copper coil of six turns, with a current of 960 A flowing through it. Water is flushed through the coil to cool it during the heating process. The half model is preferred due to symmetry, and also it can give us adequate knowledge of how the heating is being effected. The workpiece has a specific heat capacity of 516 (J/kg) $\cdot$ C and a density of 7800 kg/m^3.

In a solenoid work coil, the magnetic flux tends to concentrate toward the center, and this renders the heating rate produced in this area generally greater than that produced toward the ends.

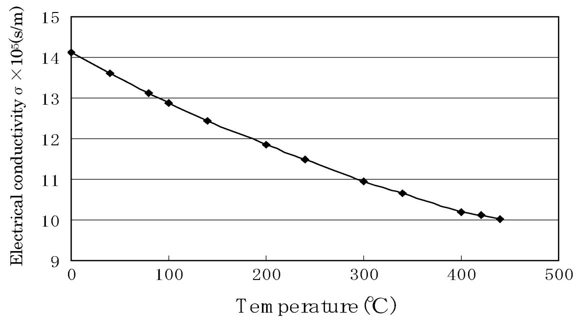

Fig. 2. Material properties for magnetic-field analysis.

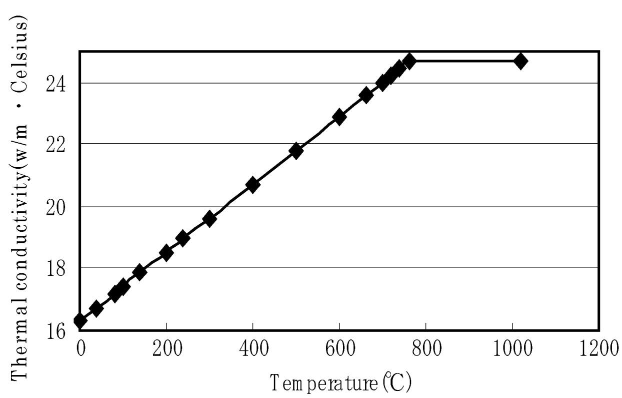

Fig. 3. Material properties for the thermal analysis.

To address this unwanted heating pattern, a proposed coil is desired to the original, as shown in Fig. 1. Optimization was done by varying d and D, which are the distances from the coil to the workpiece. Our objective was to attain some extent of uniform heating. After several modifications, optimized coil, which is the proposed coil was achieved when $d = 10$ mm and $D = 20$ mm. The original coil has its $d = 10$ mm. The space in between the coil turns was maintained as 5 mm. These and other parameters are shown in Fig. 1.

III. Computational Procedure

The 3-D frequency response analysis is used for the magnetic-field analysis, and nonsteady-state analysis is used for the thermal analysis. The reason for using frequency response analysis is that the magnetic field varies with time faster than the temperature of the workpiece. It can therefore be assumed that the magnetic field is always in a steady state for the time scale of the temperature variations. The joule loss distribution is first determined for the model, using magnetic-field analysis, which outputs the joule loss distribution as a file. This is then read for the thermal analysis and used as a heat source of the model in the thermal analysis.

The distribution of electrical conductivity is determined by temperature distribution, and the magnetic-field analysis is repeated. Therefore, for the magnetic-field analysis, calculation of the joule loss distribution as a heat source for the thermal analysis is determined. Thermal conductivity, density, and specific heat capacity are assigned to the workpiece. In the thermal analysis, calculation of temperature is determined as the local electrical conductivity for the magnetic-field analysis.

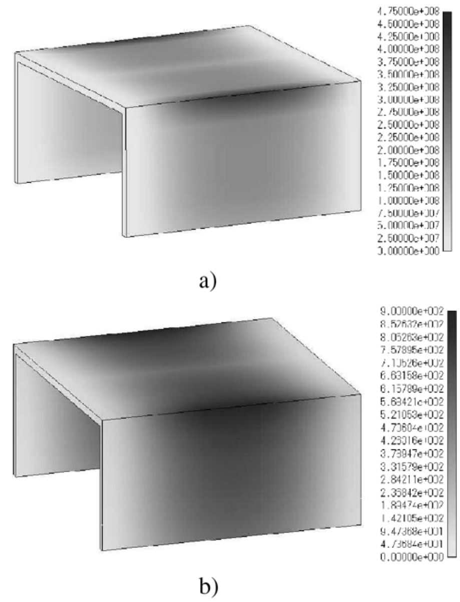

Fig. 4. Induction heating after 50 s using original coil. (a) Joule loss distribution. (b) Temperature distribution.

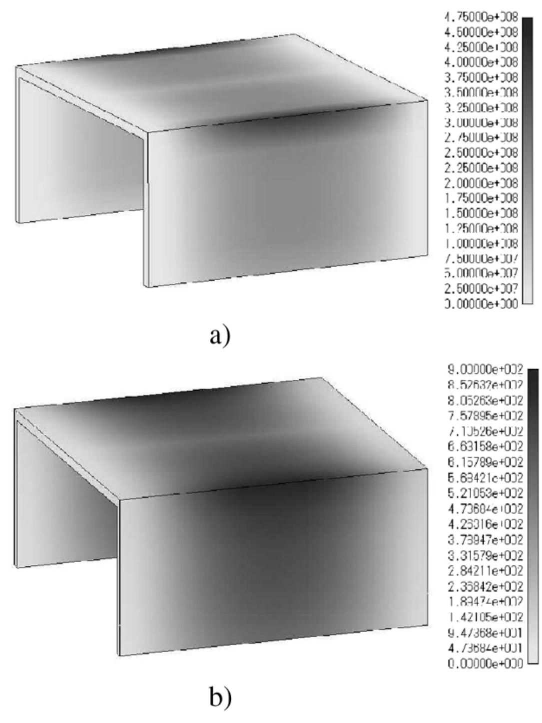

Fig. 5. Induction heating after 50 s using proposed coil. (a) Joule loss distribution. (b) Temperature distribution.

Figs. 2 and 3 show the material properties for the magnetic-field and thermal analyses, respectively. The electrical conductivity against temperature showed some sort of linearity. The thermal conductivity against temperature also showed some linearity up until around 800°, after which there was no change.

IV. Results

The results below illustrate the joule loss distribution and temperature distribution (°C) when sinusoidal currents flow in the coil at 60-kHz operating frequency. The eddy currents or the

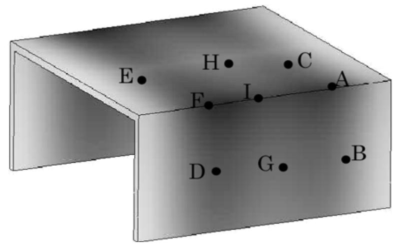

Fig. 6. Selected points on workpiece for observation.

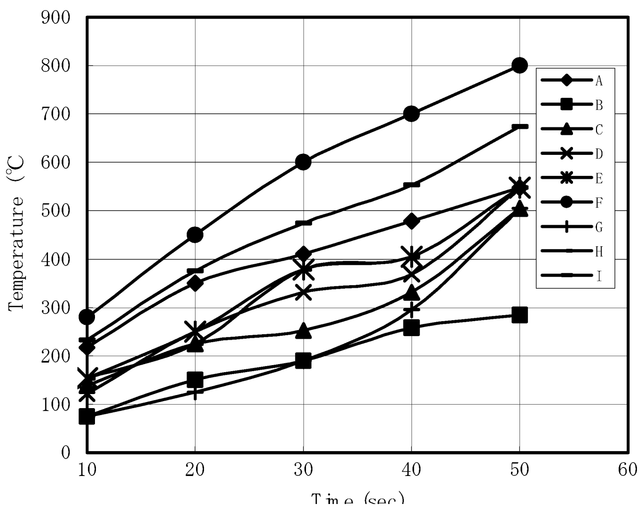

Fig. 7. Temperature variations of selected points on workpiece.

power density induced in the workpiece heated the workpiece surface slightly above 800 °C within 50 s.

The results are appreciated as an efficient heating of the surface of the workpiece has been illustrated. The bending corners of the workpiece were most heated, as the joule loss density was the highest there. The proposed coil rendered more uniform heating than the original, which had most of the heat concentrated in the center.

To ascertain our satisfaction of this work, some points on the workpiece were selected, and their temperature variations with time observed, using the proposed coil. This shows the advantage of pinpoint accuracy of induction heating. Fig. 7 shows the temperature variations at the points that are comprehensible, by their various locations on the workpiece.

Selected points showed temperature rise as time increased. The total number of nodes is 7833 and that of elements is 9200. From inference of the graph (Fig. 7), the temperature of any point on the workpiece can be predicted.

V. Conclusion

An efficient coupling technique has been demonstrated through an induction heating process using the finite-element method (FEM). The proposed coil rendered more uniform heating. Three-dimensional (3-D) simulations, though cumbersome and complicated, give us a better knowledge of the heating process and render the temperature at any point on the workpiece accessible, which would not have been possible with two-dimensional (2-D) simulations.

The techniques developed in this study can be used to predict the transient temperature distribution and power densities of the workpiece during an induction heating process and help in induction heating coil design.

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Manuscript received February 7, 2005.