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Numerical Simulation of High Frequency Induction Heating for the Design of a Casting Furnace

Hye-Jin Lee, Yoon-Sang Lee, Jae-Ho Yang, Jong-Man Park
Korea Atomic Energy Research Institute, Dukjin-Dong 150, Yesong-Gu, Daejeon, 305-353, Korea
yslee@kaeri.re.kr

1. Introduction

Induction heating is used for various applications of the industrial manufacturing process. It provides various heat treatments such as hardening, melting, casting and so on [1].

Induction heating is a complex process coupling the electromagnetic and thermal phenomena. In this process an alternating electric current induces electromagnetic field, which in turn induces eddy currents in the workpiece. The induced eddy currents release energy in the form of heat, which is then distributed throughout the workpiece [2].

In this paper, the electromagnetic and thermal coupling analysis was performed by the 3 dimensional finite elements program, OPERA 3D. For convenience of calculation, a steady-state was assumed. Based on materials composing a real smelting furnace, testing the distribution of eddy current from each material and its final temperature value, we found out which material has advantage in the temperature variations among suggested materials, and confirmed which material is suitable to composing smelting furnace.

2. Numerical Method

Numerical analysis of the induction heating requires the development of a coupling procedure between the electromagnetic and thermal problems. The eddy currents calculated from the electromagnetic solution are used as the heat sources for the thermal analysis.

2.1 Electromagnetic field

In electromagnetic analysis, the displacement currents can be neglected by magneto-quasi-static approximation [3]. Then, Maxwell's equations are

$$\nabla \times \mathbf{H} = \mathbf{J} \qquad (1)$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (2)$$
$$\nabla \cdot \mathbf{B} = 0 \qquad (3)$$

Ohm's law can be written as

$$\mathbf{J} = \sigma \mathbf{E} \qquad (4)$$

where **H** is the magnetic field, **J** the electric current density, **B** the magnetic flux density, and σ is the electrical conductivity.

From eqn. (3) the magnetic flux density can be derived from the curl operation of another vector such that

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad (5)$$

where **A** is the vector potential. Using eqns. (1)~(5), the governing equation for current density can be derived as follows, which is called the dispersion equation.

$$\sigma \frac{\partial \mathbf{A}}{\partial t} - \frac{1}{\mu} \nabla^2 \mathbf{A} = \mathbf{J}_S \qquad (6)$$

where μ is the magnetic permeability and $\mathbf{J_S}$ is the source current density in the induction coil. In order to calculate the eddy current density in the workpiece, it requires boundary conditions.

When high frequency alternating current is flowing through the coils, an eddy current is created on the surface of the workpiece. This is called the skin effect, and its average depth is called the skin depth (δ). It can be calculated as

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu \cdot \sigma}} \qquad (7)$$

where f is the frequency. The electromagnetic field exists below the skin depth [3].

2.2 Thermal field

Under stationary conditions, the temperature field distribution is described by the following equation.

$$\nabla \cdot \kappa \nabla T = -\mathbf{Q} \qquad (8)$$

where T is the temperature, κ the thermal conductivity, and **Q** the heat source density. The solution of the equation requires initial and boundary conditions at the interface between the workpiece and the air. Assuming the convection, the boundary condition is then,

$$q \cdot n = h \cdot (T - T_{ext}) \qquad (9)$$

where n is the normal vector, h the convection coefficient, T the temperature of the workpiece, and T_{ext} the ambient temperature.

3. Results

3.1 Numerical modeling

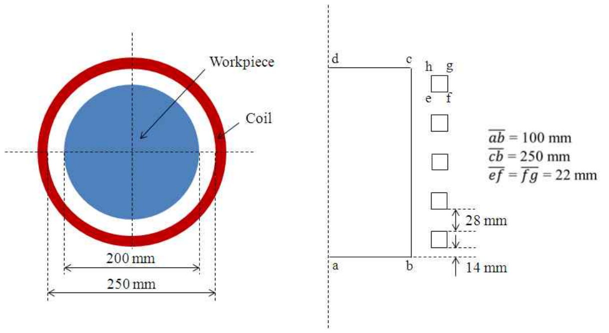

Fig. 1. The model geometry for numerical analysis

Fig. 1 shows the cylindrical model geometry. The coil is powered by Ac current source of I = 100 A and frequency f = 10 kHz. The ambient temperature is 25 °C. Material properties used for the workpiece modeling are summarized in Table I.

Table I. The numerical values of each material [4]

	Alumina	Copper	Graphite	SUS 304
Electrical Conductivity (S/m)	10^{-12}	5.88×10^{7}	16666.67	1.39×10^{6}
Thermal Conductivity (W/m·K)	46	398	24	16.2

3.2 Numerical results

Fig. 2 and 3 are the results of the electromagnetic and thermal coupling operations by OPERA 3D program which is FEM-based SW.

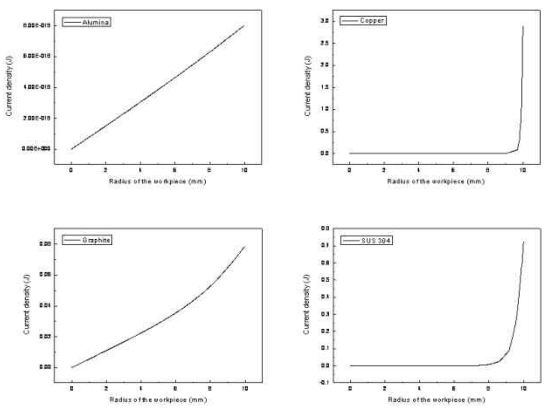

Fig. 2. The current density distribution of each material from the center to the surface in the workpiece

Fig. 2 shows the distribution of the eddy current in the workpiece from the center to the surface. In the two cases of the copper and the SUS 304, the eddy currents are formed in the surface. The graphite is linearly increasing from the center to the surface. The alumina has a very small value for the eddy current density about ~10^{-18}.

Using the above results, the temperature distribution was calculated in Figure 3. The graphite had the highest temperature at 2117.5 °C among the given materials. The alumina was similar to the ambient temperature,

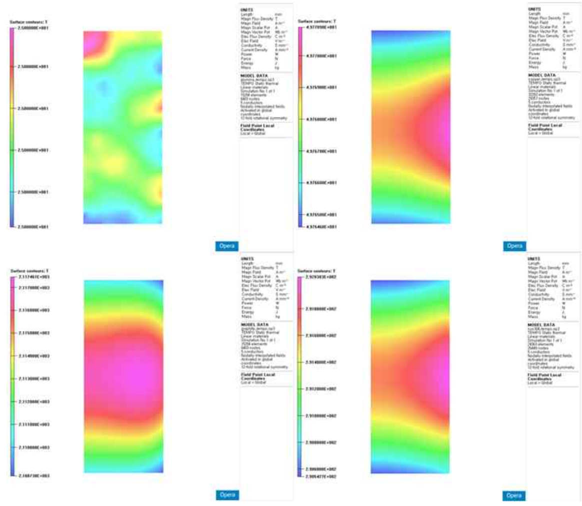

Fig. 3. Temperature distribution of the materials

which indicates that the induction heating was rarely generated. For the remaining materials, the temperature values are summarized in Table II.

Table II. Maximum temperatures of each material

	Alumina	Copper	Graphite	SUS 304
Maximum Temperature (°C)	25	49.8	2117.5	292

4. Conclusion

In this paper, using the cylindrical model geometries, the electromagnetic and thermal analysis was performed in the steady-state condition. According to the numerical results of high-frequency induction heating in this paper, the most sensitive material was the graphite, and the alumina was found to be an insensitive material. Thus, in the structure of the high-frequency induction heating furnace, the graphite is suitable as a crucible and the alumina is suitable as an insulator.

5. Acknowledgements

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