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Induction Heating Jar의 온도분포 해석에 관한 연구

A Study on the Temperature-Diffusion Analysis of Induction Heating Jar

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Abstract

Induction heating is widely used in today's industry, in operations such as metal hardening, preheating for forging operations, melting or cooking. In this paper, it was presented the magneto-thermal analysis of an induction heating jar(IH-JAR) with the material value of the stainless and the aluminum for efficient design. The magnetic field intensity inside the axisymmetric shaped cooker was analyzed using three-dimensional axisymmetric finite element method(FEM) and the effectual heat source was obtained by ohmic losses from eddy currents induced in the jar. The heat was calculated using the heat source and heating equation. Also, it was represented the temperature characteristics of the IH-JAR according to time and relative permeability in stainless parts and in aluminum parts.

Key Words : induction heating, FEM, three-dimensional axisymmetric, IH-JAR

1. INTRODUCTION

Induction heating describes the thermal conductivity problem in which the heat is generated by ohmic losses from eddy currents induced in conducting media, such as stainless steel and aluminum, by a varying magnetic field[1][2]. Induction heating is widely used in today's industry, in operations such as metal hardening, preheating for forging operations, or cooking. It is a complex process, involving both electromagnetic and thermal phenomena. Recently, induction heating jar (IH-Jar) is very interested for high efficiency, the quickness of heating time and the convenient regulation of heating spot. The magnetic field intensity and the heat source in the IH-Jar should be exactly calculated in order to make temperature distribution required on the surface of the IH-Jar. But, the waste of time and cost has been increased because the design method of the IH-Jar in the industry is depending on the experience. Therefore, it is continuously required that the development of precision design method is based on the exact magnetic field intensity and heat source[3]-[6]. In this paper, the magneto-thermal analysis of an induction heating workpiece(IH-Jar) was presented as an efficient design. The magnetic field intensity inside the axisymmetric shaped cooker was analyzed using three-dimensional axisymmetric finite element method(FEM) and the effectual heat source was obtained by ohmic losses from eddy currents induced in the jar. The heat was calculated using the heat source and heating

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equation. Also, it was represented the temperature characteristics of the IH-Jar according to time and relative permeability in stainless parts and in aluminum parts.

2. EDDY CURRENT PROBLEM

The construction of the IH-Jar can apply to the three-dimensional axisymmetric FEM because it is the same form for circular direction. We can summarize the Maxwell's equation describing the systems with eddy currents as follows equation (1)~(5).

$$\nabla \times H = J \quad (1)$$

$$J = \sigma E \quad (2)$$

$$E = -\frac{\partial A}{\partial t} - \nabla \phi \quad (3)$$

$$B = \nabla \times A \quad (4)$$

$$B = \mu H \quad (5)$$

where, H is the intensity of magnetic field, J is the sinusoidal exciting current density, σ is the electric conductivity of mass, E is the intensity of electric field, A is the magnetic vector potential, ϕ is the scalar potential, B is the magnetic flux density and μ is the permeability of mass. For the system, we can set the $\nabla\phi$ in equation(3) to zero[7], the final governing equation for A is the equation(6).

$$\frac{1}{\mu}\nabla^2 A = j\omega\sigma A - J \quad (6)$$

where, ω represents the angular frequency of the sinusoidal exciting current. The energy functional whose Euler-Lagrange equation is the same as governing equation(6) can be expressed as equation(7).

$$F = \int\int_s \frac{1}{2\mu}\left\{\left(\frac{1}{r}\frac{\partial rA}{\partial z}\right)^2 + \left(\frac{1}{r}\frac{\partial rA}{\partial r}\right)^2\right\} 2\pi r dr dz + \frac{j\omega}{2}\int\int_s \sigma A^2\, 2\pi r dr dz - \int\int_s JA\, 2\pi r dr dz \quad (7)$$

After discretizing of the system, minimization condition of the energy functional equation(7) gives the system matrix equations(8).

$$[P]\{A\} + [Q]\{A\} = \{R\} \quad (8)$$

where, [P] and [Q] are the coefficient matrices and {R} is the forcing vector. The coefficient matrices and the forcing vector can be assembled with element matrices written as equation(9)~(11).

$$[P]^e = \frac{1}{4\mu^e\triangle^e}\begin{bmatrix} b_l^2+c_l^2 & b_lb_m+c_lc_m & b_lb_n+c_lc_n \\ b_lb_m+c_lc_m & b_m^2+c_m^2 & b_mb_n+c_mc_n \\ b_lb_n+c_lc_n & b_mb_n+c_mc_n & b_n^2+c_n^2 \end{bmatrix} \quad (9)$$

$$[Q]^e = \frac{j\omega\sigma^e\triangle^e}{12}\begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} \quad (10)$$

$$[R]^e = \frac{J^e\triangle^e}{3}\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (11)$$

where, $\triangle^e$ is the area of that element.

It can be calculated the magnetic vector potential, the eddy current and the heat source in each node by solving the system matrix equation. And the eddy current, J_e , is the equation(12) from ohms law as shown below.

$$J_e = \sigma E_e = -\sigma\frac{\partial A}{\partial t} = -j\omega\sigma A \quad (12)$$

The heat source per unit volume, $ht_s[W/m^3]$, is written as equation(13).

$$ht_s = \frac{|J_e|^2}{\sigma} = \omega^2\sigma|A|^2 = \omega^2\sigma AA^* \quad (13)$$

3. FE-MODEL OF IH-JAR

Table 1 and figure 1 are respectively the three-dimensional axisymmetric FE-model of the IH-Jar and the material constants of it.

Table. 1 The material constants of the IH-Jar

	Stainless Steel	Aluminum
Relative permeability (μ_r)	1(case 1) 100(case 2) 200(case 3)	$0.25\text{x}10^{-7}$
Electric conductivity (σ)	$1.66667\text{x}10^{6}$	$4.0\text{x}10^{7}$
Thermal conductivity (k)	30	204

Figs. 2, 3 and 4are respectively the flux lines of case 1($\mu_r = 1$) , of case 2($\mu_r = 100$) and of case 3(. $\mu_r = 200$) Here we know that the flux lines cannot completely pass through the inner IH-Jar because of the skin effect of the stainless steel.

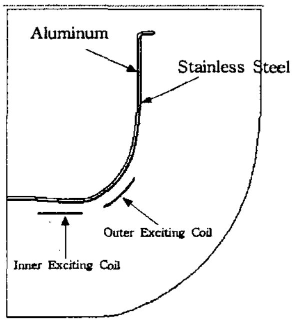

Fig. 1. The FE-model of the IH-Jar

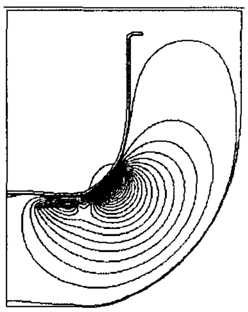

Fig. 2. The flux lines of the IH-Jar($\mu_r = 1$)

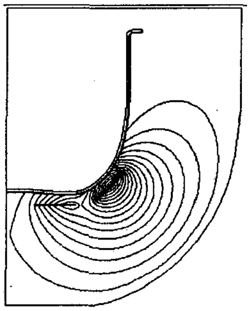

Fig. 3. The flux lines of the IH-Jar($\mu_r = 100$)

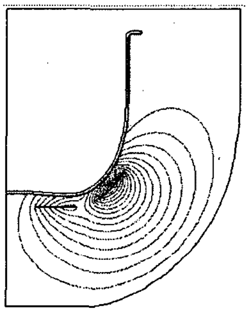

Fig. 4. The flux lines of the IH-Jar($\mu_r = 200$)

4. Temperature characteristics

Figs. 5 and 6 represent respectively the temperature characteristics of the IH-JAR according to time and relative permeability in stainless steel parts and in aluminum parts.

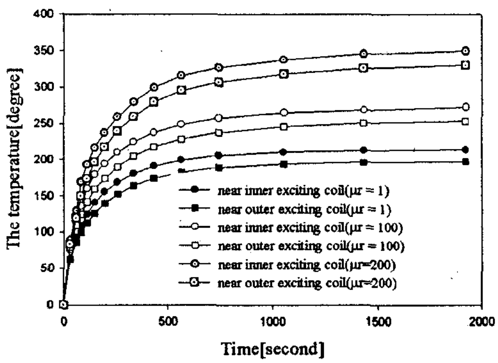

Fig. 5. The temperature curve of the IH-JAR in stainless steel.

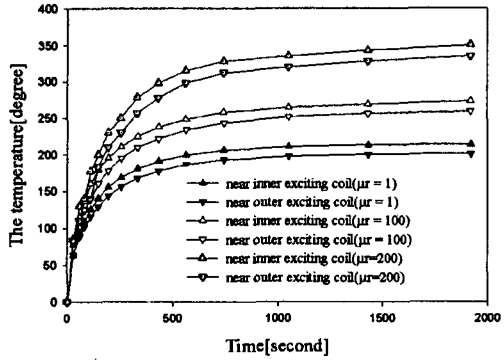

Fig. 6. The temperature curve of the IH-JAR in aluminum.

Here we know that the temperature of the IH-JAR near the outer exciting coil is larger than that at its near inner exciting coil at the initial time, and the temperature of it near the inner exciting coil is maximum at final time. The temperature of aluminum is higher than that of stainless steel at point distant from the heat source because the thermal conductivity of aluminum is larger than that of stainless steel. Also we know that the temperature of the IH-JAR is rapidly reached its peak value as the value of relative permeability is high.

5. Conclusions

In this paper, the magneto-thermal analysis of the IH-JAR was presented as an efficient design. And the magnetic field intensity inside the axisymmetric shaped cooker was analyzed using three-dimensional axisymmetric finite element method (FEM), and the effectual heat source was obtained by the calculation of the induction current in the IH-JAR. The temperature of the IH-JAR near the outer exciting coil is larger than that at near the inner exciting coil at the initial time, and the temperature near the inner exciting coil is maximum at final time. The temperature of aluminum is higher than that of stainless steel at point distant from the heat source because the thermal conductivity of aluminum is larger than that of stainless steel. The temperature of the IH-JAR rapidly reaches its peak value as the value of relative permeability is high.

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