Electromagnetic Property Evaluation on HAZ and Base Metal of Modified 9Cr-1Mo steel by Eddy Current Method

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Eddy-current method is applied to evaluate electromagnetic properties of modified 9Cr-1Mo steel used in power plants in order to investigate the material changes in heat affected zone (HAZ) and base metal in Type IV damage evaluation. A pancake-coil impedance model based on eddy current theory is proposed to evaluate conductivity and permeability of conducting material. Further more a series of HAZ and base specimens of Modified 9Cr-1Mo steel in different heat treatment conditions are experimentally measured and then their conductivity and permeability are estimated. The evaluated results show that electromagnetic properties difference between specimens in each heat treatment conditions is obvious and can be distinguished.

Keywords: Electromagnetic Properties, Eddy Current, HAZ, Base Metal, Modified 9Cr-1Mo steel

1. Introduction

High chromium ferritic steel (Modified 9Cr-1Mo steel) is a high strength structural steel widely used in power plant. In recent years, some studies for this steel have pointed out that Type IV damage, which is happened in the softened heat-affected zone (HAZ) of weldment and caused by different creep strength between weld metal, HAZ and base metal, is one of mid-life failure [1][2][3][4]. In order to investigate material changes in HAZ and base metal in high temperature service environment to prevent Type IV cracking, evaluation of the electromagnetic properties such as conductivity and permeability by non-destructive testing method is considered as one of prospecting approaches to monitor the microstructure change.

Eddy-current method is one of rapid, portable and feasible non-destructive testing to estimate conductivity and permeability, and can carry out a direct measurement of electromagnetic properties without calibration standards. In this paper, a pancake-coil impedance model is proposed, which is derived from partial differential equation. Comparing with well established theory by Dodd and Deeds [5], the present model is simplified, but can solve the "overflow" problem that sometimes occurs in the numerical calculation using Dodd's formula. The "overflow" problem occurs in the case of ferritic materials because they have higher relative permeability than linear material so that the value of some variables in Dodd's formula exceeds the maximum floating-point number of a given precision (single or double). Consequently, a series of base and HAZ specimens in different heat treatment conditions are measured by impedance analyzer. Then, their conductivity and permeability are determined by searching for an impedance match with theoretical values. The evaluated conductivity and permeability of HAZ and base metal specimen shows it is possible to use eddy-current method to evaluate electromagnetic properties of Modified 9Cr-1Mo steel.

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2. Pancake-Coil Impedance Model

For a pancake coil paralleling to a metal plate, as shown in

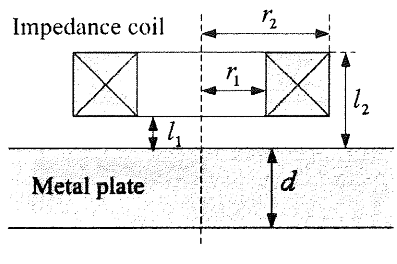

Fig.1 Pancake impedance coil model.

Fig.1, a closed-form solution in Eqs. (1) and (2) can be derived from Maxwell equations considering both ferromagnetic and non-ferromagnetic conductors by solving the magnetic vector potential A in an electromagnetic field.

$$Z=\frac{j\omega\pi\mu_0 n^2}{(l_2-l_1)^2(r_2-r_1)^2}\int_0^\infty \frac{1}{\alpha^5}I^2(r_2,r_1)\cdot[2(l_2-l_1)$$
$$+\alpha^{-1}(2e^{-\alpha(l_2-l_1)})-2+(e^{-2\alpha l_2}+e^{-2\alpha l_2}-2e^{-\alpha(l_2-l_1)})\cdot\frac{\alpha-\beta_1}{\alpha+\beta_1})]d\alpha \quad (1)$$

$$Z_{air}=\frac{j\omega\pi\mu_0 n^2}{(l_2-l_1)^2(r_2-r_1)^2}\int_0^\infty \frac{1}{\alpha^5}I^2(r_2,r_1) \quad (2)$$
$$\cdot[2(l_2-l_1)+\alpha^{-1}(2e^{-\alpha(l_2-l_1)}-2)]d\alpha$$

$$Z_{Dodd}=\frac{j\omega\pi\mu_0 n^2}{(l_2-l_1)^2(r_2-r_1)^2}\int_0^\infty \frac{1}{\alpha^5}I^2(r_2,r_1)[2(l_2-l_1)$$
$$+\alpha^{-1}(2e^{-\alpha(l_2-l_1)})-2+(e^{-2\alpha l_2}+e^{-2\alpha l_1}-2e^{-\alpha(l_2-l_1)}) \quad (3)$$
$$\cdot\frac{(\beta_1^2-\alpha^2)+(\alpha^2-\beta_1^2)e^{2\alpha d}}{-(\beta_1-\alpha)^2+(\alpha+\beta_1)^2e^{2\alpha_1 d}}]d\alpha$$

Here,

$$\beta_1=\alpha_1/\mu_r,\quad \alpha_1=(\alpha^2+j\omega\mu_0\mu_r\sigma)^{1/2},$$

and

$$I(r_2,r_1)=\alpha^2\int_{r_1}^{r_2} r_0 J_1(\alpha r_0)dr_0\,.$$

μ_0 and μ_r are permeability of free space and relative permeability of metal plate respectively. σ is conductivity of metal plate, n is the number of turns in the pancake coil, $J_1(x)$ is the first-order Bessel function of the first kind. Eq.(2) is the air-impedance without measuring a metal plate. The impedance formula in Eq.(3) was derived by Dodd and Deeds. Since experimental measurement indicated the nonlinear and hysteresis effects are fairly small for low currents, this formula can be used for ferrite material [5][6]. However, due to $\mu_r >> 1$ for ferritic material, the term of $e^{2\alpha_1 d}$ in some cases is too large so as to exceed the maximum floating-point number to cause "overflow" error. If the first term in both numerator and denominator is neglected, Eq.(3) is equivalent to Eq.(1). This means the solution in Eq.(1) that is derived from partial differential equations is accordant with Dodd and Deeds theory.

Table 1. Parameters of pancake coil

r_1	Inner radius	0.5 mm
r_2	Outer radius	1.0 mm
l_1	Lift-off	0.1 mm
l_2	Height of coil	2.1 mm
n	Number of turns	300
f	Exciting frequency	89.661 kHz
ωL_0	air-reactance	33.186 Ω
R_0	DC resistance	15.02 Ω

3. Impedance coil and experiment correction

An air-cored probe is fabricated by winding a coil. Parameters of the coil are listed in Table 1. Ten tested specimens of Modified 9Cr-1Mo steel in different heat treatment conditions are listed in Table 2. Because of the non-ideal coil behavior, two corrections have to be considered when processing the experiment data. First, in Eq. (1), the DC resistance of a coil (when $\omega=0$) is zero. However, any practical coil has DC resistance R_0 shown in Table 1. Therefore the experimental resistance $R^{\exp}$ should be corrected to match the theoretical value R^{cal} calculated by Eq.(1). The corrected resistance $R^{\exp}$ shown in Eq.(4) is that measured resistance R^{mea} minus DC resistance R_0 .

Secondly, since the coil was wound in layers, it is not an absolute ideal pancake inductance coil. The self-reactance between the measured and theoretically calculated value by Eq.(2) are different. The error between them is 1.32%. This error can be solved after normalizing the reactance by dividing the self-reactance in both calculated and measured data. In Eq.(5), ωL_0^{mea} is measured air-reactance, $X_{norm}^{\exp}$ is normalized experimental reactance. In Eq.(6), Z_{air}^{cal} is calculated air-reactance by Eq.(2), ωL^{cal} is imaginary part calculated by Eq.(1). X_{norm}^{cal} is normalized calculated reactance. At last, by seeking an approximate equal between theoretical and experimental impedance in Eqs.(7) and (8) with assumed conductivity and permeability, the evaluated

Table 2. Specimen list of Modified 9Cr-1Mo steel

Heat treatment condition	Base material Size (mm)	HAZ Size (mm)
N.A. (no heat treatment)	33×15×5t	25×15×5t
500 ^{0}C×600 hr A.C.	33×15×6t	25×15×5t
550 ^{0}C ×600 hr A.C.	33×15×5t	25×14×5t
600 ^{0}C ×600 hr A.C.	34×15×5t	25×13×4t
650 ^{0}C ×600 hr A.C.	33×15×6.5t	15×14×5t

conductivity and permeability is determined.

$$R^{\exp} = R^{mea} - R_0 \quad (4)$$

$$X_{norm}^{\exp} = j\omega L^{mea} / j\omega L_0^{mea} \quad (5)$$

$$X_{norm}^{cal} = j\omega L^{cal} / Z_{air}^{cal} \quad (6)$$

$$R^{cal} \cong R^{\exp} \quad (7)$$

$$X_{norm}^{cal} \cong X_{norm}^{\exp} \quad (8)$$

4. Experiment data

The measurement device is Hewlett Packard 4294A impedance analyzer. A low exciting current 10 mA with frequency 89.661 kHz was given to the pancake impedance coil. The induced maximum magnetic field in specimens is about 70 Gauss. The measured resistance is shown as in Fig.2. The data needs to be processed by Eq.(4) to obtain corrected experimental resistance for comparing with theoretical values. The measured reactance is shown in Fig.3. The data also needs to be normalized by air-reactance using Eq. (5). Both of corrected resistance and normalized reactance are compared with theoretically calculated value using Eq. (1). When the best match between corrected experiment value and theoretically calculated value is found with an assumed conductivity and permeability, the evaluated conductivity and permeability are accepted.

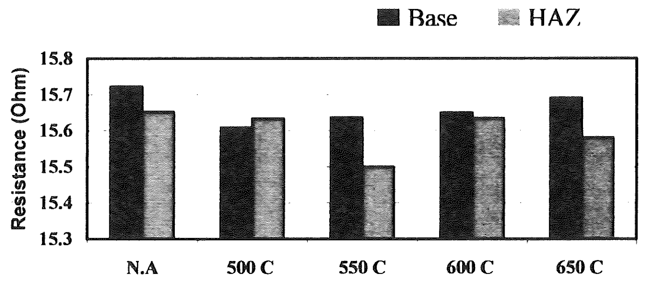

Fig.2 Measured resistance in different heat treatment conditions.

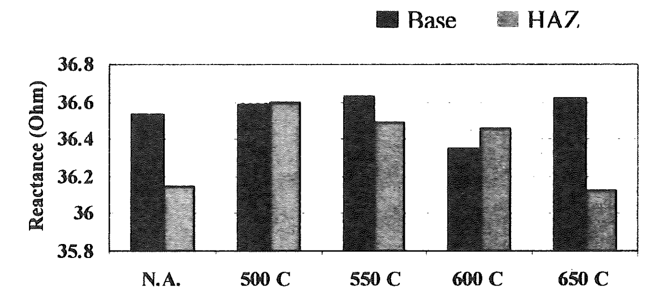

Fig.3 Measured reactance in different heat treatment conditions.

5. Evaluated results and discussion

The evaluated conductivity and permeability are shown in Figs.4 and 5 respectively. In order to validate the evaluated results, a four-terminal conductivity measurement device and magnetic measurement device SQUID were applied to measure the same specimens. The evaluated conductivities agree with the four-terminal conductivity measurement device in the same quantity level. But this device did not provide enough accuracy digital to distinguish the difference among each specimen. SQUID results also show there exist the permeability difference between these specimens. All of information to some extent supports the evaluation by the presented impedance coil model.

6. Summary

An impedance coil model is presented to evaluate the conductivity and permeability of HAZ and base metal of Modified 9Cr-1Mo steel in different heat treatment conditions. The evaluated results with the verification by conductivity and magnetic measurement devices indicate there is possibility to eddy-current method as a nondestructive testing approach to estimate the electromagnetic properties of high chromium ferric steel for predicting the microstructure change in Type IV damage investigation.

Acknowledgement

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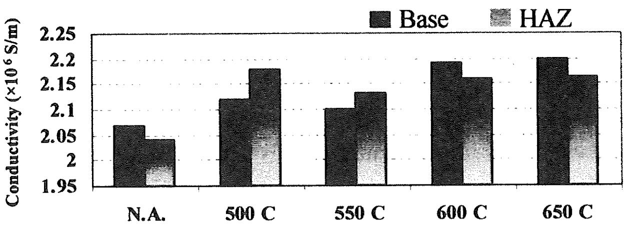

Fig.4 Evaluated conductivities of Modified 9Cr-1Mo specimens in different heat treatment conditions.

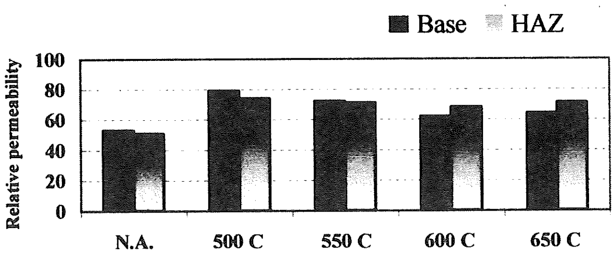

Fig.5 Evaluated permeability of Modified 9Cr-1Mo specimens in different heat treatment conditions.

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