Detection of material degradation in nuclear power plant components by Eddy current method

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ABSTRACT

Fatigue damage and neutron irradiation embrittlement of low alloy steel and thermal embrittlement of duplex stainless steel were detected using eddy current technique, changing frequency in steps of 1kHz. Output voltage from detection coil was processed by phase detection technique and displayed as a trajectory on complex Gauss plane. By comparing the trajectory of a nondegraded material with that of a degraded material, degradation was evaluated quantitatively. It was shown that neutron irradiation embrittlement increases electric conductivity, fatigue decreases electric conductivity and thermal embrittlement decreases magnetic permeability and increases electric conductivity. It was indicated that material degradation can be detected and evaluated by nondestructive method.

INTRODUCTION

Material degradation caused by aging in nuclear power plant components includes neutron irradiation embrittlement, fatigue and thermal embrittlement of duplex stainless steel. Detection of these degradation in an early stage for prevention of possible accidents may contribute to improve availability and reliability of nuclear power plants. Eddy current measurement has been widely used as one of nondestructive testing methods as both apparatus and sensor are light and compact. It also allows testing without contact of sensor with the surface of materials tested and provides excellent recordability because of the nature of electro-magnetic induction of eddy current phenomenon.

Three types of material degradation mentioned above were detected using eddy current, changing frequency in steps of 1kHz. Output voltage from detection coil was processed by phase detection technique and displayed as a trajectory on complex Gauss plane. By comparing the trajectory of a nondegraded material with that of a degraded material, degradation was evaluated quantitatively. Drawing such trajectory enables us to understand the eddy current behavior totally. Change in averaged radius or averaged phase angle of trajectory can be treated as change in magnetic permeability and/or electric conductivity of the material.

EXPERIMENTAL

Experimental Equipment

Experimental equipment consists of input current generation part for excitation coil and output voltage from detection coil processing part. The former contains direct digital synthesizer to generate a wave in numerical form and D/A converter to convert the numerical wave into electric current. The latter
contains phase detection circuit for complex number processing and A/D converter for numerical processing. Resistance component \( V_r \) and inductance component \( V_i \) are detected by processing the output voltage through phase detection circuits and are treated as real part and imaginary part of complex amount of voltage. \( V_r \) and \( V_i \) are functions of frequency. By changing frequency, point \((V_r, V_i)\) depicts trajectory on Gauss plane.

Sensor Coil

The sensor is mutual induction, self differential coil system which has one excitation coil (C-1), two detection coils(C-2A, C-2B) and a ferrite core, as show in Fig.1. Lower part of this sensor is situated vertically on the surface of specimen.

Test Specimen

Conditions for fabrication of test specimens are shown in Table 1.

Data Processing

After canceling unbalance voltage between two detection coils which develops from the shape difference of upper with lower end of the ferrite core, output voltage from degraded or nondegraded material gives trajectory shown conceptually in Fig.2. To extract features of trajectories, following two parameters were defined.

1. Averaged radius : \( r \)

The intensity of output voltage at frequency \( f_i \) is calculated as the distance \( r_i \) of the point \((V_r, V_i)\) from origin. Averaged radius \( r \) is defined by the following equation. \( N \) is the number of changes of frequency.

\[
r = \left( \frac{\Sigma \, r_i^2}{N} \right)^{1/2}
\]

(1)

2. Averaged phase angle : \( \Theta \)
Phases angle can be calculated as \( \arctan(V_i/V_r) \) for point \((V_r, V_i)\). As the difference of phase angle \( \theta_i \) of degraded material from that of standard nondegraded material at the same frequency \( f_i \) was found to be better parameter to express the degree of degradation, it is called hereafter as phase angle. Averaged phase angle \( \Theta \) is calculated by the following equation.

\[
\theta = \frac{\Sigma \theta_i}{N}
\]

(2)

EXPERIMENTAL RESULT

Neutron Irradiation Specimen

Fig.3 and 4 show trajectories of output voltage from base metal and weld metal specimen. In both figures, not remarkable changes are seen among trajectories obtained from specimen having different amount of irradiation. Averaged radius changes slightly as neutron fluence increases. Fig.5 and 6 show the behavior of phase angle as the frequency changes. Phase angles of each specimen lay in a certain horizontal band. Fig.7 shows the averaged phase angle \( \Theta \) defined by equation (2) decreases as neutron fluence increases in both case of base metal and weld metal.
Ductile-brittle transition temperature \( v_{\text{T50}} \) defined through Charpy impact test has been measured for these materials, and the averaged phase angle \( \Theta \) were plotted for \( v_{\text{T50}} \) as shown in Fig.8. These figures show that the transition temperature increases and the averaged phase angle decreases as the material become brittle by the increased amount of neutron irradiation. [1]

Fatigue Specimen

Fig.9 shows trajectories of output voltage of specimens fatigued by bending in the range of \( N/N_{25} \) from
0 to 100%, where N is number of cyclic loading and N_{25} is number of cyclic loading at which the load decreases to 25% of initial load of strain-controlled fatigue testing. Change in trajectories obtained from fatigued specimens was not considerable for every test specimen having different N, N_{25} or type of loading (bending or tension-compression). Averaged radius changed slightly in every specimen. Fig.10 shows the behavior of phase angle as the frequency increases. Fig.11 shows the behavior of averaged phase angle $\theta$ as $N/N_{25}$ increases. Fig.12 shows that of specimens fatigued by tension-compression loading. It is clear that $\theta$ increases as $N/N_{25}$ increases in both figures.

**Thermal Embrittlement Specimen**

Fig.13 shows the trajectory of output voltage obtained from CF8M (Ferrite content : 25%) specimens thermally aged at 450°C for 0 to 10000 hours. Trajectory changes remarkably as aging hour increases.

In order to express the degree of thermal aging by single parameter, equivalent operational year $t_e$ was introduced through next equation derived from the assumption that thermal embrittlement obeys Arrhenius type of equation.

$$t_e = t \cdot \exp \left( \frac{Q}{R \cdot T_2} - \frac{Q}{R \cdot T_1} \right)$$

(3)

where $t$: aging hour, $T_1$: aging temperature ($^\circ$ K), $T_2$: plant operational temperature (=$325^\circ$C=$598^\circ$ K; PWR), $Q$: activation energy (=$21000$cal/mol), $R$: gas constant (=$2$cal/mol/$^\circ$ K)

Averaged radius $r$ and averaged phase angle $\theta$ are plotted as function of equivalent operational year $t_e$ in Fig.14 and 15. It is clear that these parameters decrease as equivalent operational year increases.

These parameters are also plotted as function of absorbed energy measured through Charpy impact test in Fig.16 and 17. Using these figures for standard correlation curve, absorbed energy is expected to be estimated from eddy current measurement.

**ANALYSIS FOR EXPERIMENTAL RESULTS**

**Analytical Solution**

Impedance $Z$ for unit length of cylindrical coil of infinite length having co-centrically cylindrical test specimen whose electric conductivity is $\sigma$ and magnetic permeability is $\mu$ is known to be expressed by the following equation when the input current wave form is sinusoidal, generated by constant current source:

$$Z = \psi Z_0$$

$$\psi = (1-\eta)^+ 2 \eta \mu \mu_0 I_0(qb) / \mu_0 \phi \phi \phi_0(qb)$$

$$Z_0 = \pi \omega L_0, \quad L_0 = \pi \mu_0 N^2 / a^2, \quad \eta = (b/a)^2, \quad q = (j \mu_0 \sigma \omega)^{1/2}$$

(4)

where $a$ is coil radius, $b$ : specimen radius, $N$ : coil windings in unit length, $\omega = 2 \pi f$, $f$ : frequency of electric current, $I_0$, $I_1$ : deformed Bessel function of 0-th or 1-st order, $\mu_0$ : magnetic permeability of vacuum, and $j$ : unit of imaginary number.

In case of constant voltage source as used in practical eddy current examination, output voltage $V$ of finite length coil can be expressed by the following equations:

$$V = \psi V_0 Z_0 / Z_1$$

$$Z_0 = Z_0, \quad Z_1 = R_1 + j \omega L_1$$

(5)

where $V_0$ is constant input voltage for coil, $l$: coil length, $R_1$ : resistance of coil, $L_1$ : inductance of coil.

For mutual induction, self differential coil used in this experiment, output voltage from detection coil $V$ can be expressed by the same equation as (5) substituting $\psi$-s in place of $\psi$, where $s$ stand for the output voltage from upper detection coil (C-2B), i.e.
Calculation of Trajectory

In order to calculate $V$ and depict its trajectory using equation (6), material properties of test specimens $\sigma$ and $\mu$ should be given. For the thermally embrittled test specimens, $\sigma$ and $\mu$ were measured and shown in Table 2. Substituting these values and coil dimensions into equation (6), trajectories are calculated and shown in Fig. 18.

In low frequency region (upper half of the plane), coincidence of calculated value with experimental value is good. In high frequency region (lower half), experimental value has to be evaluated taking the coil characteristic into consideration as the characteristic frequency of the coil is designed to be 32 kHz.

Fig. 19 shows the effect of $\sigma$ or $\mu$ on the trajectory. From this figure, it is clear that averaged radius $r$ increases as $\mu$ increases and averaged phase angle $\bar{\theta}$ increases as $\sigma$ decreases.

CONCLUSION

In order to detect and evaluate such material degradation as neutron irradiation embrittlement of low alloy steel for reactor pressure vessel, thermal embrittlement of duplex stainless steel for primary cooling systems and general fatigue of components in nuclear power plants, eddy current technique has been developed which adopt mutual induction, self differential coil as sensor, processing system having voltage supply of variable frequency through direct digital synthesizer and evaluate material degradation through output voltage trajectory from which averaged radius and averaged phase angle are extracted. Based on the analytical solution of impedance of infinite length coil, equations giving output voltage from finite length coil with constant voltage source was derived and its trajectory was depicted.

From experimental and analytical results, following conclusions are obtained:

(1) Averaged phase angle of trajectory decreases as the neutron fluence increases in irradiation embrittlement specimen of low alloy steel. This result shows that by neutron irradiation electric conductivity increases. Transition temperature can be estimated from measurement of averaged phase angle. [2]

(2) Averaged phase angle of trajectory increases as the number of cyclic loading increases in fatigue specimen of low alloy steel. This result shows that by fatigue electric conductivity decreases. Number of cyclic loading can be estimated from measurement of averaged phase angle.

(3) Averaged radius and averaged phase angle decrease as equivalent operational year increases in thermal embrittlement specimen. This result shows that by thermal embrittlement electric conductivity increases and magnetic permeability decreases. Absorbed energy can be estimated from measurement of averaged radius or averaged phase angle.

(4) Calculated value from equations which give output voltage for specified electric conductivity and magnetic permeability coincides with experimental value in low frequency region.

(5) It was verified that material degradation could be detected and evaluated quantitatively using nondestructive method as eddy current technique.

REFERENCES
2. Blaszkieivicz, M. 1995. The development of nondestructive evaluation (NDE) for monitoring the embrittlement in nuclear pressure vessels. 7th Int. Symp. on Nondestructive Characterization of Materials, Prague : Czech Republic
Table 1 Fabrication Condition
(a) Neutron Irradiation Specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>SA533 Gr.B cl. 1 Base metal and Weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor for</td>
<td>Material Testing Reactor of New York State University or Michigan State University</td>
</tr>
<tr>
<td>Irradiation</td>
<td></td>
</tr>
<tr>
<td>Neutron Flux</td>
<td>$8 \times 10^{14}$ n/m$^2$/sec ($E &gt; 1$ Mev)</td>
</tr>
<tr>
<td>Neutron Fluence</td>
<td>$5 \times 10^{22}$ n/m$^2$, $3 \times 10^{23}$ n/m$^2$ ($E &gt; 1$ Mev)</td>
</tr>
<tr>
<td>Temperature</td>
<td>290°C</td>
</tr>
</tbody>
</table>

(c) Thermal Embrittled Specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF8M (SCS14A : JIS G5121)</td>
<td>A</td>
</tr>
<tr>
<td>Ferrite Content 10%</td>
<td></td>
</tr>
<tr>
<td>Ferrite Content 25%</td>
<td>B</td>
</tr>
<tr>
<td>CF8 (SCS13A : JIS G5121)</td>
<td>C</td>
</tr>
<tr>
<td>Aging Temperature</td>
<td>350°C, 400°C, 450°C</td>
</tr>
<tr>
<td>Aging Hour</td>
<td>$0, 3 \times 10^8, 1 \times 10^9, 3 \times 10^9, 1 \times 10^9, 3 \times 10^9$</td>
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</table>

Table 2 Characteristics of Thermal Embrittled Specimen

<table>
<thead>
<tr>
<th>Aging hour</th>
<th>Relative Magnetic Permeability</th>
<th>Electric Conductivity (S/m)</th>
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<tbody>
<tr>
<td>0</td>
<td>82</td>
<td>$1.452 \times 10^6$</td>
</tr>
<tr>
<td>3000</td>
<td>51</td>
<td>$1.519 \times 10^6$</td>
</tr>
<tr>
<td>10000</td>
<td>33</td>
<td>$1.572 \times 10^6$</td>
</tr>
</tbody>
</table>

(b) Fatigue Specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>SA508 cl. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Tension/compression or 4 Point Bending</td>
</tr>
<tr>
<td>Environment</td>
<td>Room Temperature, in Air</td>
</tr>
<tr>
<td>$N_s$ and Strain range</td>
<td>$N_s$ Strain Range</td>
</tr>
<tr>
<td></td>
<td>$10^3$ $\pm$ 1.0%</td>
</tr>
<tr>
<td></td>
<td>$10^4$ $\pm$ 0.40%</td>
</tr>
<tr>
<td></td>
<td>$10^5$ $\pm$ 0.26%</td>
</tr>
<tr>
<td>$N/N_s$</td>
<td>$0 \sim 100%$ (Several Points)</td>
</tr>
</tbody>
</table>

Fig. 1 Mutual Induction, Self Differential Coil

Fig. 2 Feature Extraction

Fig. 3 Trajectory of Output Voltage from Neutron Irradiation Specimen (Base Metal)

Fig. 4 Trajectory of Output Voltage from Neutron Irradiation Specimen (Weld Metal)
Fig. 5 Phase Angle Distribution in Neutron Irradiation Specimen (Base Metal)

Fig. 6 Phase Angle Distribution in Neutron Irradiation Specimen (Weld Metal)

Fig. 7 Averaged Phase Angle vs. Neutron Fluence in Neutron Irradiation Specimen

Fig. 8 Averaged Phase Angle vs. Transition Temperature in Neutron Irradiation Specimen

Fig. 9 Trajectory of Output Voltage from Fatigue Specimen (Bending, N_{25}=10^5)

Fig. 10 Phase Angle Distribution in Fatigue Specimen (Bending, N_{25}=10^5)
Fig. 11 Averaged Phase Angle vs. N/N_{25} in Fatigue Specimen (Bending)

Fig. 12 Averaged Phase Angle vs. N/N_{25} in Fatigue Specimen (Tension/Compression)

Fig. 13 Trajectory of Output Voltage from Thermal Embrittlement Specimen (CF8M, 450°C)

Fig. 14 Averaged Radius vs. Eq. Op. Year in Thermal Embrittlement Specimen (CF8M, 450°C)

Fig. 15 Averaged Phase Angle vs. Eq. Op. Year in Thermal Embrittlement Specimen (CF8M, 450°C)

Fig. 16 Averaged Radius vs. Absorbed Energy in Thermal Embrittlement Specimen (CF8M)

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Fig. 17 Averaged Phase Angle vs. Absorbed Energy in Thermal Embrittlement Specimen (CF8M)

Fig. 18 Comparison of Calculated Value (Curve) with Experimental Value (●, ■, △)

Fig. 19 Parametric Study of Trajectory

(a) $\sigma = (1 \sim 10) \times 10^6$ (S/m), $\mu_m = 80$

(b) $\mu_m = (10 \sim 100)$, $\sigma = 1 \times 10^6$ (S/m)