Proposed Method for Simultaneous Inspection of Lift-off and Surface-hardened Depth in Induction-hardened Steel Plate Using Electromagnetic Properties

Tsubasa Yoshinaga,1* Yuji Gotoh,2 Shun Onita,3 Takashi Horino,3 and Yoshitaka Misaka3

1Department of Mechanical and Energy Systems Engineering, Oita University, 700 Dannoharu, Oita 870-1192, Japan
2Department of Innovative Engineering, Faculty of Science and Technology, Oita University, 700 Dannoharu, Oita 870-1192, Japan
3Research and Development Headquarters, Neturen Co., Ltd., 141-8639, Japan

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The evaluation of surface-hardened depth ($D$) in induction-hardened steel is important in the guarantee of quality of the steel. If the size of the surface-hardened steel is large, a nondestructive evaluation method is required to inspect the $D$ since destructive testing using, for example, a Vickers hardness tester, becomes difficult. The electromagnetic properties of the hardened layer are different from those of the nonhardened layer in surface-hardened steel. Therefore, it is possible to estimate the $D$ of surface-hardened steel by measuring the difference in these electromagnetic characteristics using an electromagnetic sensor. On the other hand, the detection signal in the electromagnetic sensor is also affected by the distance (lift-off: $L_o$) between the surface of the hardened steel and the sensor. In this paper, a method for simultaneously measuring the $D$ in a hardened steel plate and $L_o$ is proposed. The usefulness of simultaneous measurement using the proposed inspection method is evaluated by a 3D nonlinear finite element method taking account of the initial $B$–$H$ (magnetic flux density: $B$, magnetic field strength: $H$) curve and the conductivity of the layers with and without hardening in the surface-hardened steel. In addition, an experimental verification is also carried out.

1. Introduction

Because steel can be hardened in a short time, induction-hardened steel is used for axles of large motors, crankshafts of automobiles, railway rails, and large bearing parts of large generators, and so forth. In induction hardening, the depth of the hardened layer is adjusted via the excitation frequency of the induction coil in the induction hardening device. Since the mechanical properties, such as abrasion resistance and fatigue resistance, of the induction-hardened steel change with the surface-hardened depth ($D$), it is necessary to evaluate the $D$ of...
the steel. Generally, the $D$ of surface-hardened steel is measured by destructive testing using a Vickers hardness tester, Brinell hardness tester, Rockwell hardness tester, and so forth. If the size of the surface-hardened steel is large, such destructive testing becomes difficult. Therefore, there is a demand for a nondestructive inspection method that is compact and can evaluate the $D$ without contact. As nondestructive inspection methods for the $D$, the ultrasonic method, alternating current potential drop method, and Barkhausen noise method have been proposed. Since a contact medium or measurement electrodes are required by the ultrasonic method and the alternating current potential drop method, noncontact inspection is difficult. Barkhausen noise testing requires high detection performance and signal processing technology since the detection signal is weak.

In this paper, we propose a nondestructive inspection method for the $D$ in the surface of an induction-hardened steel plate using only a steady alternating magnetic field and a simple device. The $D$ of the steel plate is measured by detecting the difference in the permeability and conductivity between the hardened and nonhardened layers inside the steel plate using an electromagnetic sensor by an eddy current testing method. On the other hand, in the actual field, it is difficult to maintain the distance (lift-off: $L_0$) between the surface of the induction-hardened steel and the sensor with high accuracy. This is because the surface of the induction-hardened steel may have a thin nonmetallic coating of unknown thickness such as a rust preventive. Moreover, the thickness of this coating is not uniform. However, the detection signal is also influenced by minute changes in $L_0$. Therefore, in this research, we propose a method for simultaneously measuring the $D$ in a hardened steel plate and $L_0$ that is not affected by minute fluctuations in $L_0$.

2. Electromagnetic Properties of Steels with and without Hardening in High-frequence Hardened Steel

In this research, the $D$ is evaluated only for SCM440 steel, which is often used in machine parts. Generally, the maximum $D$ for machine parts is about 5 mm. Therefore, in this paper, the maximum $D$ to be considered is 5.5 mm. This is a chromium molybdenum steel containing 0.38 to 0.43% carbon. Figure 1 shows the hardness distribution inside the induction-hardened SCM440 steel plate as measured by a Vickers hardness tester when the effective surface-hardened depths are 1, 3, and 5.5 mm. In addition, this figure shows the average value of any five locations of each hardened depth steel plate. In this figure, the horizontal axis shows the depth from the surface in the surface-hardened steel plate and the vertical axis shows the Vickers hardness value at the test load of 0.3 kg. In the Japanese Industrial Standards (JIS), the domain where the hardness inside the surface-hardened steel is harder than 400 HV is defined as an effectively hardened layer. This figure shows that in the surface-hardened steel of each $D$, the maximum hardness (the hardest domain in the surface) is about 650 HV; the hardness of the intermediate layer drops sharply, and the hardness in the nonhardened domain is about 275 HV. Then, the hardened layer of 650 HV and the nonhardened layer of 275 HV in the surface-hardened steel are cut out by electrical discharge machining, and the electromagnetic characteristics of each material are measured.
Figure 2 shows the initial magnetization curves of the hardened (650 HV) and nonhardened (275 HV) layers of SCM440 steel. This figure shows that the permeability of the steel is reduced by hardening.\(^{10}\) The conductivities of the hardened and nonhardened layers in the surface-hardened steel are also measured to be $3.231 \times 10^6$ and $3.983 \times 10^6$ S/m, respectively. Both the maximum relative permeability and conductivity of the hardened layer are lower than those of the nonhardened layer.

3. Inspection Model and Calculation Method

3.1 Electromagnetic inspection model

Figure 3 shows the inspection model for detecting both the $D$ in the surface-hardened steel plate and the $L_o$ between the electromagnetic sensor and the steel plate. The inspection model is symmetrical about the $x$-axis regarding the $x$-$y$ plane, so the model is shown halved. In this paper, a flat plate is used as the induction-hardened steel material for basic research. The proposed electromagnetic sensor consists of an electromagnetic yoke made of laminated silicon steel plate, an alternating excitation coil, and two detection coils. The excitation frequency and current applied to the excitation coil are 10 Hz and 1.5 A (rms), respectively. The flux density ($B_z$) inside the magnetic yoke is detected with the $z$-direction detection coil on one leg of the yoke, and the $x$-direction magnetic field ($B_x$) distributed between the two legs of the yoke is detected with the $x$-direction detection coil. These $B_x$ and $B_z$ are evaluated on the basis of the peak values of these waveforms. The surface of induction-hardened steel may be coated with a nonmetallic layer of an unknown thickness such as paint or rust preventive. Therefore, it is difficult to know the exact value of $L_o$ in the actual inspection. In this research, both the $L_o$ and $D$ are estimated using $B_x$ and $B_z$ detected by the two detection coils.
3.2 Method of analysis considering interpolation of magnetization curves and conductivities

In this research, the flux densities \( B_x \) and \( B_z \) in the two detection coils are analyzed by the 3D electromagnetic finite element method (FEM) taking account of the initial magnetization curve and the conductivity of the layers with and without hardening in the surface-hardened steel plate. Since the applied magnetic flux is small for the electromagnetic yoke in this electromagnetic sensor, the relative permeability is calculated at a constant 1000 × \( \mu_0 \) H/m. Since the magnetic yoke is made of laminated silicon steel sheets, the eddy currents in the magnetic yoke are neglected.

The 3D FEM with first-order hexahedral edge elements are applied. To obtain steady-state results, the computations are performed over three periods (= 96 steps). The time interval \( \Delta t \) of the step-by-step method is chosen as 3.125 × 10^{-3} s when the excitation frequency is 10 Hz. The basic equations of the electromagnetic field analysis in consideration of the eddy current using the \( A-\varphi \) method are given by

\[
\text{rot}(\nu \text{rot} \, A) = J_o - \sigma \left( \frac{\partial A}{\partial t} + \text{grad} \, \varphi \right),
\]

where \( A \) is the magnetic vector potential, \( \nu \) is the reluctivity, \( J_o \) is the current density, and \( \sigma \) is the conductivity.
\[
\text{div} \left\{ -\sigma \left( \frac{\partial A}{\partial t} + \text{grad} \phi \right) \right\} = 0,
\]

where \( A \) is the magnetic vector potential, \( \phi \) is the scalar potential, \( v \) is the reluctivity, \( J_0 \) is the current density, and \( \sigma \) is the conductivity. The Newton–Raphson (N–R) method is used for the nonlinear iterative calculation of the magnetic characteristic. The N–R iterative calculations are performed using the initial magnetization curve shown in Fig. 2. The conditions for the calculations and measurements are shown in Table 1.

The inside of the surface-hardened steel is divided into a hardened layer, a heat-affected zone, and a nonhardened layer. Therefore, to calculate the flux density inside the hardened steel, a nonlinear electromagnetic field analysis that considers the magnetization curve and the conductivity in these three layers is required. Figure 4 shows an example of the hardness distribution inside the surface-hardened steel plate when the effective hardened depth \( D \) is 3

Table 1

| Conditions of calculation and measurement. |
|---------------------------------------------|
| Excitation coil | Excitation frequency: 10 Hz, Ampere-turns: 1.5 A (rms) \times 60 turns = 90 AT |
| Search coil (\( B_x \)) | \( x \)-direction of magnetic field: 175 turns |
| Search coil (\( B_z \)) | \( z \)-direction of magnetic field: 95 turns |
| Lift-off (\( L_o \)) | 0.1, 0.15, 0.2, 0.25, 0.3 mm |
| Dimension of specimen | SCM440 steel plate 120 \times 230 \times 20 mm\(^3\) |
| Hardened depth (\( D \)) | 0, 1, 3, 5 mm |
| Conductivity | Hardened domain: \( 3.23 \times 10^6 \) S/m Non-hardened domain: \( 3.98 \times 10^6 \) S/m |
| Nodes and elements | 86436, 78182 |
| Convergence criterion | N–R method: \( 1.0 \times 10^{-4} \) T, ICCG method: \( 1.0 \times 10^{-4} \) |

Fig. 4. (Color online) Example of hardness distribution inside surface-hardened steel plate when the effective hardened depth \( D \) is 3 mm.
mm. The figure shows that the hardness from the surface in the steel plate to 2.75 mm is about 650 HV. Since the region between the depths of 2.75 and 3.25 mm is the heat-affected zone, the hardness is reduced almost linearly from 650 to 275 HV. The hardness of the region deeper than 3.25 mm is almost constant at about 275 HV. Therefore, in the nonlinear FEM analysis, the initial $B$–$H$ (magnetic flux density: $B$, magnetic field strength: $H$) curve and conductivity of the hardened layer shown in Fig. 2 with a hardness of 650 HV are used for the region from the surface of the hardened steel plate to 2.75 mm, and in the region deeper than 3.25 mm inside the steel plate, the initial $B$–$H$ curve and conductivity of 275 HV of the nonhardened layer in Fig. 2 are used. On the other hand, the initial $B$–$H$ curve and conductivity in the heat-affected zone from 2.75 to 3.25 mm depth are obtained by linear interpolation using the magnetization curve and conductivity of the 650 HV hardened layer and the 275 HV nonhardened layer.

### 3.3 Effects of hardened depth and change in lift-off

The distribution of the flux density inside the steel plate is analyzed when the $D$ and $L_o$ are changed. Figure 5 shows the distribution of the flux density in the steel plate when $L_o$ is constant at 0.1 mm and $D$ is 0 and 5.5 mm. This figure shows that since the permeability and conductivity are lower in the surface-hardened region than in the nonhardened region, the maximum flux density inside the steel plate is decreased when $D$ is increased. Figure 6 shows the effect of $D$ on

![Diagram](image)

**Fig. 5.** (Color online) Distribution of the flux density in the steel plate when the surface-hardened depth $D$ is 0 and 5.5 mm ($L_o = 0.1$ mm). (a) Display domain. (b) $D = 0$ mm ($B_{\text{max}} = 0.905$ T). (c) $D = 5.5$ mm ($B_{\text{max}} = 0.555$ T).
the calculated flux density $B_z$ in the $z$-direction detection coil when $L_o$ is constant at 0.1 mm. This figure shows that $B_z$ is decreased when $D$ is increased. This is because the flux density inside the magnetic yoke is decreased when $D$ is increased since the permeability and conductivity are lower inside the surface-hardened layer of the steel plate than in the nonhardened layer. Figure 7 shows the effect of $D$ on the calculated flux density $B_x$ in the $x$-direction detection coil when $L_o$ is constant at 0.1 mm. This figure shows that $B_x$ is increased when $D$ is increased. This is because the leakage flux distributed in the air between both feet of the yoke is increased since the permeability and conductivity in the surface domain of the steel plate are decreased when $D$ is increased.

Figure 8 shows the distribution of the flux density inside the steel plate when the $D$ is set to 0 mm and the $L_o$ is 0.1 and 0.3 mm. This figure shows that if $D$ is constant, the maximum flux density in the steel plate is decreased when $L_o$ is increased. This is because it becomes difficult for the magnetic flux from the excitation coil to reach the steel plate when $L_o$ is increased. Figure 9 shows the effect of $L_o$ on the calculated flux density $B_z$ in the $z$-direction detection coil when $D$ is constant at 0 mm. This figure shows that if $D$ is constant, then $B_z$ in the $z$-direction detection coil is also decreased when $L_o$ is increased, similar to the result in Fig. 6. Therefore, from the results of Figs. 6 and 9, it is difficult to inspect $D$ using only $B_z$ in the $z$-direction detection coil in the actual field.

Figure 10 shows the effect of the $L_o$ on the calculated flux density $B_x$ in the $x$-direction detection coil when the $D$ is constant at 0 mm. This figure shows that $B_x$ is increased when $L_o$ is increased, similar to the result in Fig. 7. This is because the impressed magnetic flux from the magnetic yoke is less able to penetrate into the steel plate, and the magnetic flux distributed between the two legs of the yoke is increased. Therefore, from the results of Figs. 7 and 10, it is difficult to inspect $D$ using only $B_x$ in the $x$-direction detection coil in the actual field. However, from the above results, the changes in $B_x$ and $B_z$ are different when only $D$ is changed and when only $L_o$ is changed. Therefore, a method for estimating both $D$ and $L_o$ is considered using the results for both $B_x$ and $B_z$. 

Fig. 6. Effect of surface-hardened depth $D$ on flux density $B_z$ when lift-off $L_o$ is constant at 0.1 mm (calculated).
Fig. 7. Effect of surface-hardened depth $D$ on flux density $B_x$ when lift-off $L_o$ is constant at 0.1 mm (calculated).

Fig. 8. (Color online) Distribution of flux density inside steel plate when lift-off $L_o$ is 0.1 and 0.3 mm ($D = 0$ mm). (a) Display domain. (b) $L_o = 0.1$ mm ($B_{max} = 0.905$ T). (c) $L_o = 0.3$ mm ($B_{max} = 0.323$ T).

Fig. 9. Effect of lift-off $L_o$ on flux density $B_x$ when surface-hardened depth $D$ is constant at 0 mm (calculated).

Fig. 10. Effect of lift-off $L_o$ on flux density $B_x$ when surface-hardened depth $D$ is constant at 0 mm (calculated).
4. Method of Measuring Both Surface-hardened Depth and Lift-off

The x-direction flux density $B_x$ and z-direction flux density $B_z$ obtained in each detection coil are measured when $D$ in the surface-hardened steel plate is changed for each $L_o$. Figure 11 shows the measured $B_x$ and $B_z$ in the x- and z-direction detection coils obtained by changing $D$ and $L_o$. In this figure, $B_x$ is shown on the vertical axis and $B_z$ is shown on the horizontal axis. This figure shows that if $L_o$ is constant, then $B_x$ is increased and $B_z$ is decreased when $D$ is increased. The changes in $B_x$ and $B_z$ with $D$ showed a similar trend to the results of the 3D FEM. On the other hand, if $D$ is constant, then $B_x$ is increased and $B_z$ is decreased when $L_o$ is increased. This is because $B_z$ in the closed magnetic path between the magnetic yoke and the steel plate is reduced when $L_o$ is increased, and $B_x$ distributed between both legs of the yoke is increased.

The figure shows that the changes in the signals of $B_x$ and $B_z$ due to the changes in $D$ and $L_o$ can be distinguished in this model. In this research, the unknown $D$ and $L_o$ are both evaluated by linear interpolation using the values in Fig. 11 with the measured $B_x$ and $B_z$ in the two detection coils. Table 2 shows the results of $D$ and $L_o$ obtained by interpolation using the $B_x$-$B_z$ plane of Fig. 11. For the "measured hardened depth" values in Table 2, the measurement results of the specimens as shown in Fig. 1 are shown. The measured values are almost in agreement with the obtained ones. The table illustrates that both $D$ and $L_o$ can be detected from $B_x$ and $B_z$ in the two detection coils in this model.

| Factors          | Measured | Interpolated | Error (mm) |
|------------------|----------|--------------|------------|
| Depth $D$ (mm)   | 1        | 0.92         | 0.08       |
| Lift-off $L_o$ (mm) | 0.15     | 0.133        | 0.017      |
| Depth $D$ (mm)   | 3        | 2.62         | 0.38       |
| Lift-off $L_o$ (mm) | 0.15     | 0.185        | 0.035      |
| Depth $D$ (mm)   | 3        | 2.88         | 0.12       |
| Lift-off $L_o$ (mm) | 0.25     | 0.184        | 0.066      |
| Depth $D$ (mm)   | 5.5      | 5.35         | 0.15       |
| Lift-off $L_o$ (mm) | 0.25     | 0.177        | 0.073      |

Fig. 11. $B_x$ and $B_z$ in the x- and z-direction detection coils obtained by changing surface-hardened depth $D$ and lift-off $L_o$ (measured).
5. Conclusions

The results obtained are summarized as follows:
(1) It is possible to estimate the hardened depth $D$ of a surface-hardened steel plate by detecting the change in flux density due to the differences in the permeability and conductivity in the steel with and without hardened layers. However, the flux density detected by each detection coil is influenced by the changes in both the lift-off $L_o$ and depth $D$ of the surface-hardened steel.

(2) The flux density $B_x$ in the $x$-direction detection coil is increased and the flux density $B_z$ in the $z$-direction detection coil is decreased when $D$ or $L_o$ of the induction-hardened steel is increased. However, the changes in the signals of $B_x$ and $B_z$ in the two detection coils due to the changes in $D$ and $L_o$ can be distinguished. Therefore, it is possible to inspect both $D$ and $L_o$ by detecting both $B_x$ and $B_z$ of the two detection coils in the proposed inspection sensor.

The elucidation of details of the physical phenomena leading to changes in the permeability and conductivity of the hardened steel due to induction hardening and the effects of material and shape changes on induction-hardened steel in the proposed inspection method are future research subjects. The evaluation of different materials or hardened depths deeper than 5 mm in this inspection method is a future research subject.

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