

Magnetic evaluation of hardening effect for carbon steel

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A hardening method can increase hardness of steel at the risk of increasing its brittleness. Therefore, estimations of hardness and hardening depth are very important. We clarified the magnetic properties of hardened carbon steel depending on hardening depth with cut-out hardened carbon steel rings, and proposed some electromagnetic methods to evaluate hardness and hardening depth instead of the conventional mechanical tests. However, it was difficult to evaluate quantitatively hardness and hardening depth with high accuracy. In this paper, we propose a new magnetic sensor to measure magnetic properties in hardened carbon steel plates from outside. The magnetic properties of hardened carbon steel plates under different hardening temperature conditions are examined. The results show that influence of hardening temperature on the hysteresis loss and the eddy current loss is large and we can improve estimation accuracy of hardness and hardening depth by using the new magnetic sensor.

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1. Introduction

From view points of safety and reliability of mechanical parts, it is required for industry to use steel, which has high strength and endurance. Carbon steel has been used as a lot of mechanical parts. The carbon steel, which requires high strength, is usually hardened with high frequency induction heating. However, the hardening method can increase hardness of steel at the risk of increasing its brittleness. Therefore, evaluation of hardness and hardening depth is very important for applications. Conventionally, mechanical hardness tests such as the Vickers hardness test have been used to estimate hardness and hardening depth. However, the evaluation of hardness and hardening depth for real products is very difficult because the specimens must be destroyed for measurements.

In the previous works, we examined the magnetic properties of cut-out ring specimens and clarified difference of the magnetic property depending on the hardening depth [1]. Furthermore we proposed to evaluate hardness and hardening depth of carbon steels by using electromagnetic methods instead of the mechanical tests [2-3].

Firstly, we try to detect change of eddy current inside hardened carbon steel plates by using a pick-up coil to evaluate hardening depth. In the excitation and evaluation, we proposed to employ the multi-frequency excitation and spectrogram (MFES) method [5-6]. The spectrogram obtained from the pick-up coil voltage changed for different hardening conditions. However, the quantitative estimation of hardness and hardening depth was difficult from the measured data.

Secondly, we focused on direct measurement of the magnetic flux density B and magnetic field strength H to evaluate hardness and hardening depth, because plenty of

information inside the hardened steel could be obtained. Those were the permeability, the coercive force, the residual magnetic flux density and the magnetic power loss. The magnetic properties were changed accordance with the hardening conditions of temperature and time. We try to estimate the hardening conditions by changing the exciting frequency, which has a correlation for the penetration depth. However it was difficult to clarify the relationship between the hardening condition and the magnetic properties.

In this paper, we propose to use a new magnetic sensor utilizing the Rogowski-chatotock coil in evaluation of B and H in hardened carbon steel plates. We have examined to find out an effective parameter in order to evaluate hardness and hardening depth. The results show that influence of hardening temperature on the hysteresis loss W_h and the eddy current loss W_e is large and we can improve estimation accuracy of hardening depth by using the new magnetic sensor.

2. Magnetic properties of ring specimen

2.1. Cut-out ring specimen

Fig. 1(a) shows a cylindrically hardened carbon steel, which has the hardening depth of 2 mm. The cut-out ring specimens depending on depth were made by cutting from the cylinder carbon steel as shown in Fig. 1 (b). The five ring specimens are cut out by a wire electrical discharge machine in order to keep the original properties. Table 1 shows the dimension of the cut-out ring specimens and

definition of their names.

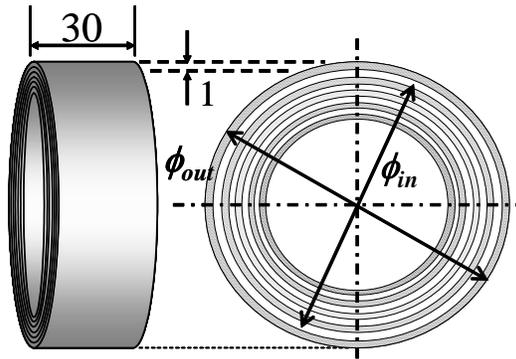


Fig 1. Operation method of cut-out ring specimen (Hardening depth : 2 mm).

Fig. 1. (a) Cylindrically hardened carbon steel.

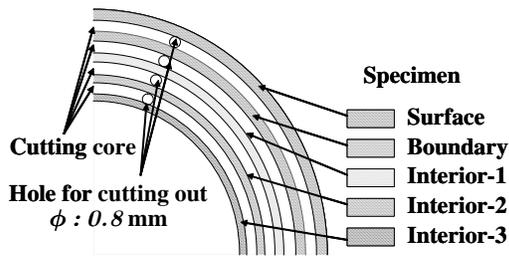


Fig. 1. (b) Cut-out method of ring specimen.

Table 1. Dimension of ring specimens.

| Name | Outer diameter [mm] | Inner diameter [mm] | Depth from surface [mm] |
|------------|---------------------|---------------------|-------------------------|
| Surface | 98.5 | 96.5 | 0-1 |
| Boundary | 94.5 | 92.5 | 2-3 |
| Interior-1 | 90.5 | 88.5 | 4-5 |
| Interior-2 | 86.5 | 84.5 | 6-7 |
| Interior-3 | 82.5 | 80.5 | 8-9 |

The DC magnetic properties of the cut-out ring specimens were measured with a DC measurement device (Yokogawa, Type 3257). The AC magnetic properties were also measured with a B-H analyzer (Iwatu, SY-8216).

2.2. Magnetic properties under DC field

Fig. 2 shows the hysteresis loops of the three cut-out ring specimens named Surface, Boundary and Interior-1. The hysteresis loops of the cut-out ring specimens of Internal-1, Internal-2 and Internal-3 were very similar. The measured hysteresis loops of the Surface and the Boundary changed very much in comparison with one of the Interior-1. It was clear that the coercive force of the

Surface increases by hardening.

We calculated also the hysteresis loss, W_h of the hardened carbon steel from the measured magnetic properties. W_h can be written as

$$W_h = \frac{1}{\rho} \Phi_1 H \delta B \quad (1)$$

where, ρ is material density. Fig. 3 shows the comparison of W_h with the Vickers hardness depending on the depth. It was clear that W_h and the Vickers hardness change depending on the depth from the surface. In particular, W_h and the Vickers hardness at the surface became large by hardening. We can confirm that by using the correlation between W_h and the hardness, we can evaluate hardness and hardening depth.

2.3. Magnetic properties under AC field

It is well known that penetration depth of magnetic flux changes due to not only exciting frequency but also material property. In the case of the hardened carbon steel, it was difficult to estimate the penetration depth of magnetic flux because the magnetic properties changed depending on the depth as shown in Figs. 2 and 3. Therefore, it is important to clarify the relationship between the frequency and the magnetic properties depending on depth in order to estimate hardness by controlling the penetration depth in sensing.

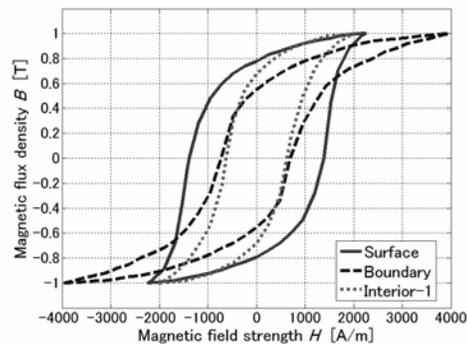


Fig. 2. Hysteresis loops of cut-out ring specimens.

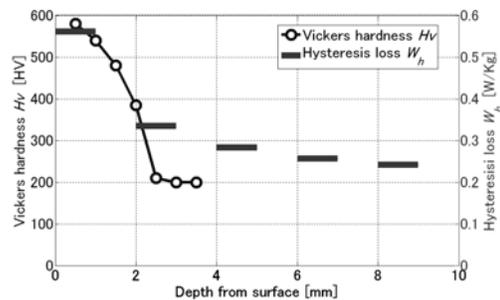
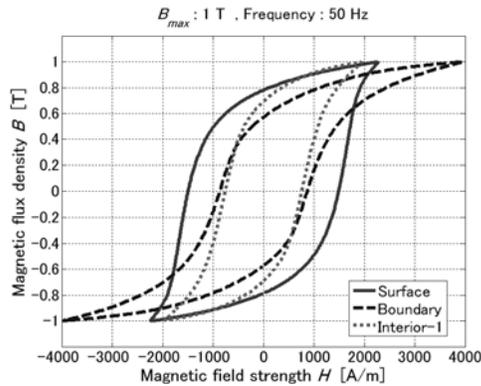


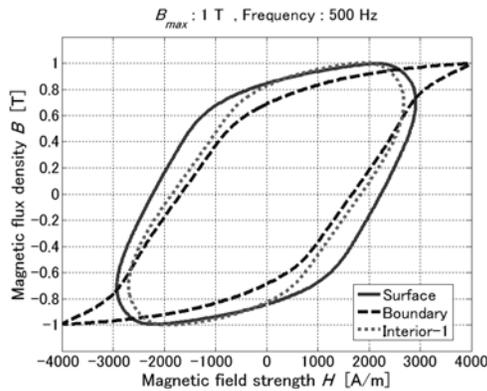
Fig. 3. Hysteresis loss depending on depth.

Fig. 4 shows the hysteresis loops of the cut-out ring specimen under AC field.



(a) $f = 50 \text{ Hz}$, $B_m = 1.0 \text{ T}$

Fig. 4. Hysteresis loops of cut-out ring specimen under A.C. field. Fig. 4 (a) $f = 50 \text{ Hz}$, $B_m = 1.0 \text{ T}$.



(b) $f = 500 \text{ Hz}$, $B_m = 1.0 \text{ T}$.

In the low frequency, the coercive force of the Surface corresponds to the hysteresis loop under DC field. In the high frequency, the area of the hysteresis loops is larger in comparison with that of the low frequency, because the eddy current becomes larger by increasing the frequency. In general, W_h and W_e are included in the magnetic power loss W_m , which is calculated as area of the hysteresis loop under AC field. As mentioned previously, it is clear that the hysteresis loss under DC field changes depending on the hardening depth. We can suppose that an effective parameter to evaluate hardness and hardening depth can be obtained by separating W_h and W_e from W_m . W_m can be written as,

$$W_m = \frac{1}{\rho f} \Phi_1 H dB \quad (2)$$

where, f is the frequency. Fig. 5 shows the measured magnetic power loss of the cut-out ring specimen under AC field. W_m increased with increasing frequency.

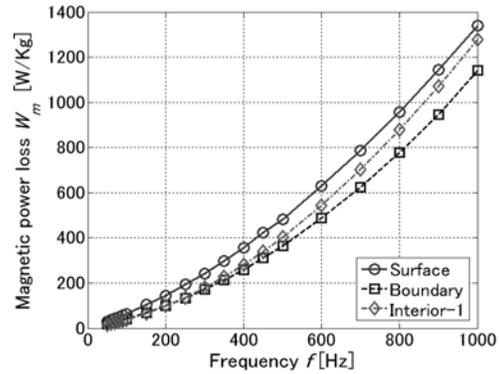


Fig. 5. Magnetic power losses W_m of cut-out ring specimen.

To examine influence of hardening conditions on W_h and W_e , we separate W_h and W_e from W_m . In general, the relationships between W_h and W_e can be written as follows,

$$\begin{aligned} W_m &= W_h + W_e \\ &= w_h f + w_e f^2, \end{aligned} \quad (3)$$

where, w_h is the hysteresis coefficient and w_e is the eddy current coefficient, respectively. Equation of W_m divided by f is given by

$$\frac{W_m}{f} = w_h + w_e f. \quad (4)$$

Fig. 6 shows W_m / f curve. As shown in this figure, W_m / f increases in proportion to the frequency according to (4). It is therefore possible to find out the value of w_h by using (4) and Fig. 6, when the frequency is equal to 0 Hz. The value of w_h becomes constant independent from the frequency, and the hysteresis loss is given by w_h and the frequency. We can also calculate W_e from w_h and Fig. 6.

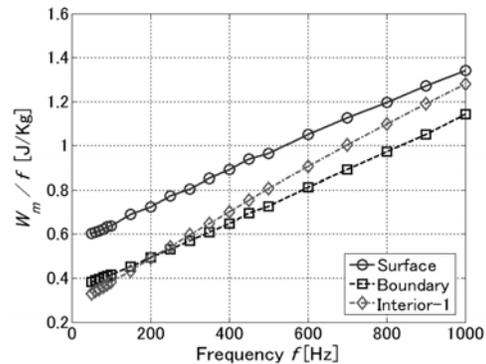


Fig. 6 Magnetic power loss per frequency W_m / f v.s. frequency f .

Fig. 7 shows W_e of the cut-out ring specimen. In high frequency case, W_e of the each cut-out ring specimen is different. In particular, W_e of the Surface decreases by

hardening. We can suppose that the eddy current of the Surface decreases because the conductivity decreases by hardening.

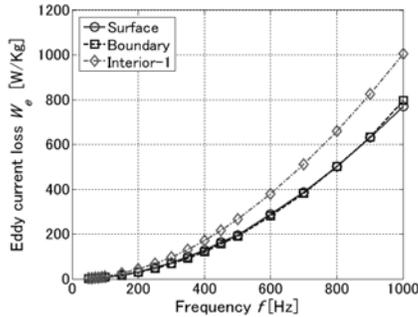


Fig. 7. Eddy current losses W_e of cut-out ring specimen.

Fig. 8 shows the relationship between W_h and W_e , which depends on the depth from the surface, at $f = 500$ Hz. W_h and W_e of the cut-out ring specimens changed depending on the depth from the surface.

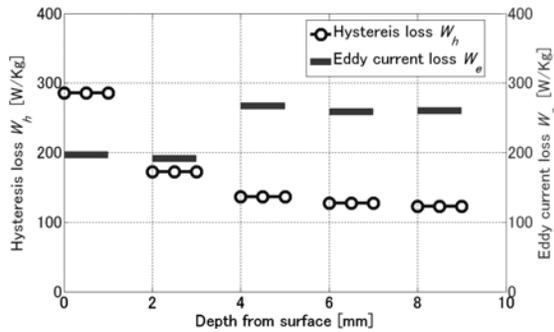


Fig. 8 Relationships between hysteresis loss and eddy current loss depending on depth ($f = 500$ Hz, $B_m = 1.0$ T).

W_h increased and W_e decreased as the depth got larger, due to influence of the hardening. W_h and W_e separated from W_m give us an effective information on hardening depth.

3. Magnetic evaluation of hardened carbon steel plates

a. Hardened Carbon Steel Plates

Fig. 9 shows the schematic view of the carbon steel specimen (S45C) used in the measurement. The central part of the specimens is hardened by using a high frequency induction heating method until the required temperature is achieved. Table 2 shows the hardening conditions. The specimens were rapidly cooled in water after heating. The hysteresis loops are measured at the

central part of the hardened steel.

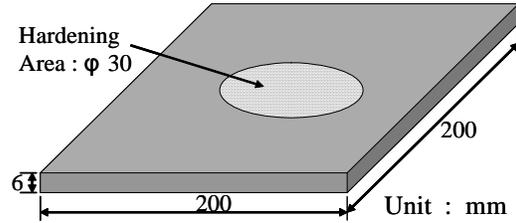


Fig. 9. Dimension of hardened carbon steel plates.

Table 2. Hardening conditions of carbon steel plate.

| Hardening temperature [°C] | Cooling method |
|----------------------------|----------------|
| Non-hardened | Water |
| 600 | |
| 760 | |
| 900 | |

b. Structure of Magnetic Sensor

Fig. 10 shows the structure of the developed magnetic sensor.

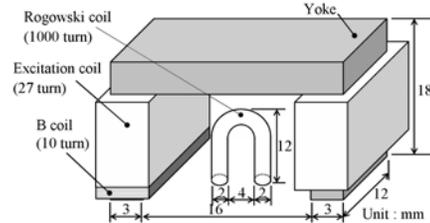


Fig. 10. Structure of magnetic sensor.

The flux density, B in the B-coil is written as follows,

$$B = -\frac{1}{N_B S_B} \int e_B dt, \quad (5)$$

where, N_B is the number of turns of the B-coil, S_B is the area of the B-coil region, e_B is the induced voltage of the B-coil, respectively. In the measurement, B in the B-coil was controlled to be 0.4 T. The field strength, H inside the specimen is measured by using the Rogowski-coil for high accurate measurement. H is written as follows,

$$H = -\frac{\ell_s}{\ell_{eff}} H_s, \quad (6)$$

where, ℓ_s is the length of the Rogowski-chattock coil, ℓ_{eff} is the effective magnetic length, H_s is the magnetic field strength in the Rogowski-chattock coil, respectively. Additionally, we can obtain the following equation,

$$H_s = -\frac{1}{\mu_0 N_H S_H} \int e_H dt, \quad (7)$$

where, N_H is the number of turns of the Rogowski-chattock coil, S_H is the area of the Rogowski-chattock coil, μ_0 is the permeability in free space, e_H is the induced voltage of the Rogowski-chattock coil, respectively. The number of turns of the Rogowski-chattock coil was 1000 turns to increase the S/N ratio. H in the local hardened area can be evaluated effectively because the proposed magnetic sensor is very compact. The hysteresis loops at any measuring point can be obtained from the relationship between B and H .

c. Measurement System

Fig. 11 shows a block diagram of the measurement system. We begin the measurement process by entering the initial parameters describing the excitation waveform with a personal computer (PC). The excitation voltage waveform generated with a wave generator is supplied to the exciting coil through a power amplifier. The induced voltages from B-coil and the Rogowski-chattock coil are transferred to the PC after digitization with a high speed and high resolution A/D converter. H and B are calculated by the measured voltage waveforms.

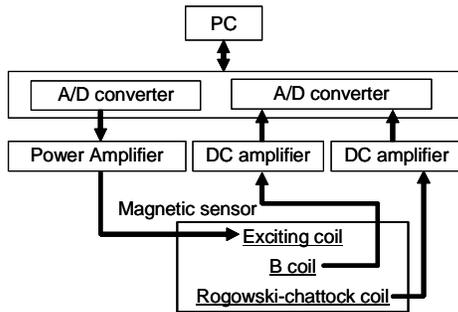
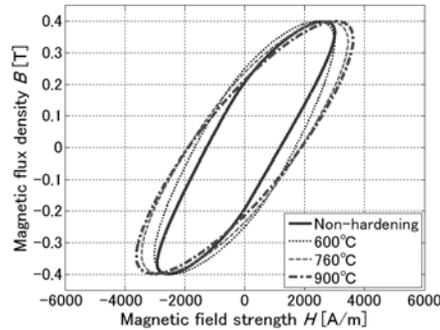


Fig. 11. Block diagram of measurement system.

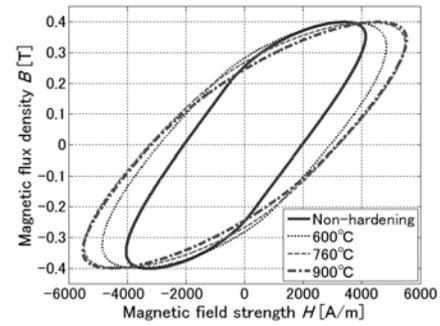
d. Magnetic Properties of Hardened Carbon Steel Plates

The excitation frequency is changed from 25 Hz to 400 Hz per 25 Hz. Fig. 12 shows the measured hysteresis loops for the different hardening temperature and frequency by using the magnetic sensor. The measured hysteresis loops were different from each other. The areas of the hysteresis loops got larger with increasing the excitation frequency, because the eddy current inside the specimen increased. The inclination of the hysteresis loops decreased with increasing the hardening temperatures as shown in Fig. 12 (a) and (b). We can suppose that the

magnetic permeability in the hardened steel becomes lower as the hardening temperature increases.



a



b

Fig. 12. Hysteresis loops of hardened carbon steel plates. (a) $f = 100$ Hz, (b) $f = 400$ Hz.

As shown in the above, the difference of the magnetic properties depending on the hardening temperatures was obtained in the measurement. In the next step, we try to find out an effective parameter, which can distinguish different of the hardening temperature. We examined the relationships between W_h and W_e obtained from the measured hysteresis loops. Fig. 13 and Fig. 14 show the measured W_m and W_m/f curves of the hardened carbon steel plates, respectively. As shown in Fig. 14, W_m/f was not in linear proportion to frequency like observed for the cut-out ring specimens.

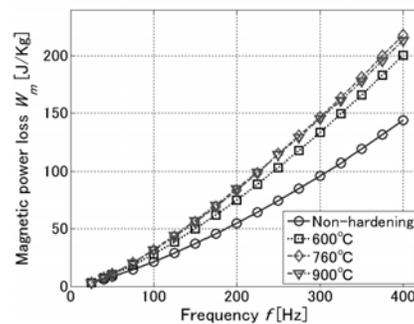


Fig. 13. Magnetic power loss W_m of hardened carbon steel plates.

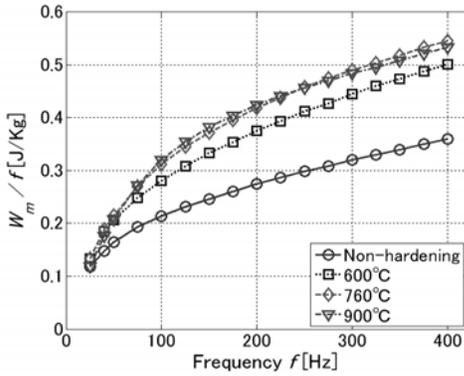


Fig. 14. W_m/f curves of hardened carbon steel plates.

The reasons can be considered that the thick carbon plates were not magnetized uniformly and the magnetic properties varied in the depth direction. Fig. 15 shows the estimation method of w_h^{fn} at $f = 0$. Since the W_m/f curves were not linear, we estimated w_h^{fn} by extrapolation with two measured points as shown in Fig. 15.

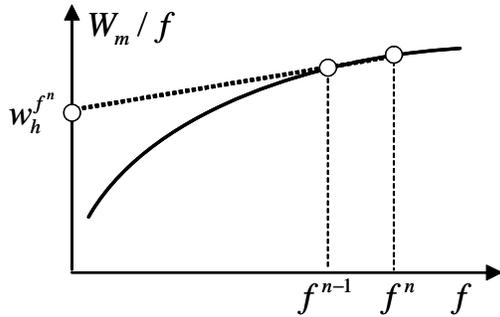


Fig. 15. Estimation method of hysteresis coefficient w_h^{fn} .

Fig 16 shows the calculated w_h^{fn} curves of the hardened carbon steel plates. The polynomial approximation was used in smoothing w_h^{fn} curves. After that, W_h and W_e were estimated by (3). Fig. 17 shows the estimated W_h and W_e .

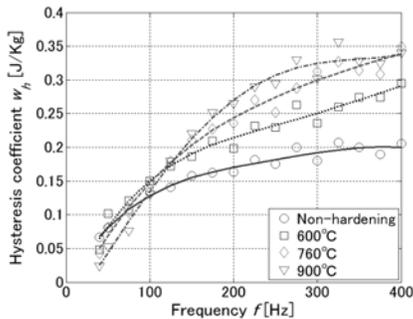


Fig. 16 Estimated hysteresis coefficient w_h^{fn} v.s. frequency.

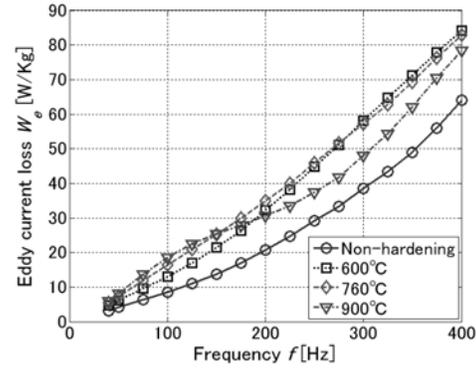
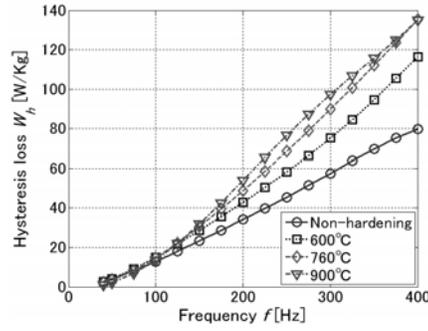


Fig. 17. Estimated magnetic properties v.s. frequency. (a) Estimated hysteresis loss W_h v.s. frequency. (b) Estimated eddy current loss W_e v.s. frequency.

In the case of the non-hardened plate, the value of W_h and W_e became small in comparison with ones of the hardened carbon steel plates, because no internal strains. In the case of the high frequency excitation, w_h^{fn} has information of the surface, because the magnetic flux concentrates near the surface of the plates. It is clear that the W_h tends to increase and W_e tends to decrease with increasing of the hardening temperature. In the case of the low frequency excitation, the magnetic flux penetrates deeply inside the hardened carbon steel plates. For the high hardening temperature, the permeability was small and the magnetic flux density inside the hardened carbon plates decreased. The difference of W_h and W_e at the different hardening temperature can be obtained by estimating w_h^{fn} . The measurement in wider frequency range needs to evaluate effects of hardening temperature. W_h and W_e were useful to estimate hardening conditions.

4. Conclusions

In this paper, we have examined W_h and W_e of the cut-out ring specimen to evaluate hardness and hardening depth by using the new magnetic sensor. The results obtained in this paper can be summarized as follows,

(1) W_h and W_e of the cut-out ring specimen changed depending on the depth from the surface. It is possible to evaluate hardness and hardening depth by using the

changes of W_h and W_e .

(2) The hysteresis loops inside the hardened carbon steel plates for the different hardening temperatures were measured by using the new magnetic sensor. The measured hysteresis loops were different from each other depending on the hardening temperature and the exciting frequency.

(3) W_h and W_e of the hardened carbon steel plates changed depending on the hardening temperatures. W_h and W_e separated from W_m give us an effective information on hardening conditions.

(4) In the future works, we will measure the real hardened product by using the developed magnetic sensor, and evaluate hardness and hardening depth from obtained W_h and W_e .

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