Proposal of leakage flux inspection method for detecting hardened depth in surface hardened steel using 3-D nonlinear FEM

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Abstract- The surface hardening steel is used for the many parts of engine or crankshaft in automobile. The inspection of the surface hardened depth is important in the intensity or the guarantee of quality of these parts. Especially, in order to raise the productivity of these parts, the non-destructive inspection method is needed for the evaluation of the hardened depth. The permeability and the conductivity of the hardened layer are smaller than the non-hardened layer in the steel. Therefore, the non-destructive estimation of the surface hardened depth is possible by using the differences of these electromagnetic properties. In this paper, the high sensitivity inspection method using the detecting of the leakage flux on the surface of the steel is investigated. The leakage flux is estimated by 3-D nonlinear finite element method (FEM) taking account of the magnetic characteristics of the layers with and without hardening. The usefulness of this proposal inspection method is shown also from comparison with a experimental verification.

***Index Terms*— 3-D non-linear finite element method, hardened depth, surface hardening steel**

I. INTRODUCTION

THE surface hardening steel is used for automobile parts. The inspection of the hardened depth of surface hardening steel of automobile parts is very important in the intensity or the guarantee of quality. Especially, in order to raise the productivity of the parts, the non-destructive and the non-contacting inspection method is needed for the evaluation of the hardened depth. The permeability and conductivity of the hardened layer are decreased compared with those of the layer without hardening. Therefore, the evaluation of the hardened depth is possible by detecting the difference of the electromagnetic characteristics [1]. The magnetic yoke with an exciting coil in which the closed magnetic circuit is formed between the specimen is approached to the surface hardened steel plate, and the inspection method for hardened depth of detecting change of the total flux density inside the magnetic yoke is proposed [2,3]. However, the inspection sensitivity of the hardened depth using this technique is not so high.

In this paper, the high sensitivity inspection method of the hardened depth of surface hardening steel plate by detecting the leakage flux of surface steel plate (SCM440) using the low frequency magnetic field is investigated [4]. The B-H curves and conductivity of the layer with and without hardening of the steel are measured. Then, the evaluation of the flux density and eddy current between the layer with and without hardening inside the surface hardening steel is estimated by the 3-D nonlinear FEM. In this nonlinear FEM, the B-H curve and conductivity inside the middle layer between the layer with and without hardening is calculated taken into consideration of linear interpolation using these electromagnetic properties. The usefulness of this proposal inspection technique is shown from comparison with the conventional inspecting method [2,3]. In addition, the experimental verification of this method is carried out.

II. INSPECTION MODEL AND CALCULATION METHOD

Fig.1 shows the 1/2 domain of the proposed the inspection model for evaluating hardened depth in the surface hardening steel plate (SCM440). This inspection probe is composed of the magnetic yokes (lamination of silicon steel plates) with an exciting coil, and two search coils. As for a search coil-A in this probe, the x-direction of leakage flux (B_x) on the surface of the steel plate is detected. Moreover, as for a search coil-B in the probe, the flux density (B_z) inside the magnetic yoke is detected. The arrangement of this search coil-B is the conventional inspection method [2,3]. The comparison of the inspection sensitivity with these search coils A and B is evaluated. The distance (lift-off : L_o) between the probe and the surface of steel tube is equal to 0.5mm. The exciting frequency and ampere-turns are 15Hz and 126AT, respectively. Fig.2 shows the B-H curves of the layer with and without hardening of the steel [5]. The conductivities of the steel plate with and without hardening are 3.61×10^6 S/m and 3.98×10^6 S/m, respectively. The permeability and

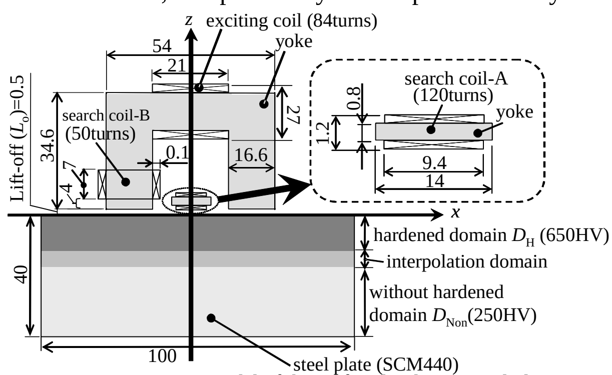


Fig.1. Inspection model of the surface hardening steel plate.

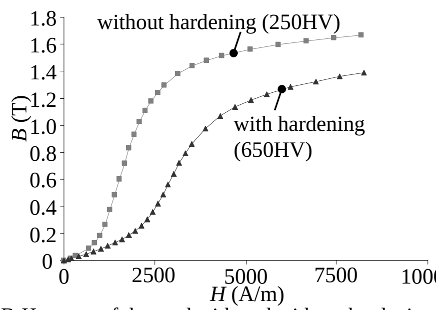


Fig.2. B-H curves of the steel with and without hardening (SCM440).

conductivity are decreased with the increase of the hardness. 3-D FEM using the 1st order hexahedral edge element is applied. The flux and eddy current are analyzed by the step-by-step method taking account of B-H curves of the layers with and without hardening as shown in Fig.2. The B-H curve and conductivity in the hardened area, non-hardened area and region between them area is obtained as follows:

Fig. 3 shows an example of the measurement result of the hardness using the Vickers hardness tester when the hardening depth is 3mm. The figure denotes that the hardness in 2.75 mm depth from the surface is about 650HV, the hardness in the domain from 2.75mm to 3.25mm depth is decreased rapidly, and that of more than 3.25mm depth becomes about 250HV. The B-H curve of the domain from 2.75mm to 3.25mm depth is obtained by the linear interpolation using the B-H curves of the layer with (0mm-2.75mm depth) and without hardening (more than 3.25mm depth). The conductivity σ in the region from 2.75mm to 3.25mm is also interpolated similarly.

III. Inspection of Hardened Depth in Steel Plate

Fig.4 shows the distribution of leakage flux B_x near a search coil-A and flux density inside surface hardened steel plate when the hardened depth is equal to 0mm and 3mm, respectively. This figure denotes that leakage flux B_x is increased when the hardened depth is increased. This is, because the leakage flux B_x from the impression magnetic field is increased since the permeability and conductivity in surface domain in steel plate is decreased when the hardened depth is increased. Fig.5 shows the effect of the hardened depth on the absolute value of the change rate of $|B_x|$ and $|B_z|$ in these search coils A and B. The figure denotes that $|B_x|$ and $|B_z|$ are increased when the hardened depth is increased. Moreover, $|B_x|$ is larger than $|B_z|$. As for $|B_x|$ in the search coil-A, the calculated result is in agreement with measurement. Therefore, the usefulness of detection of leakage flux $|B_x|$ was shown in this figure.

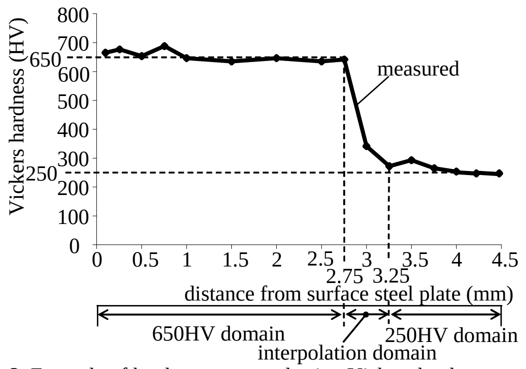
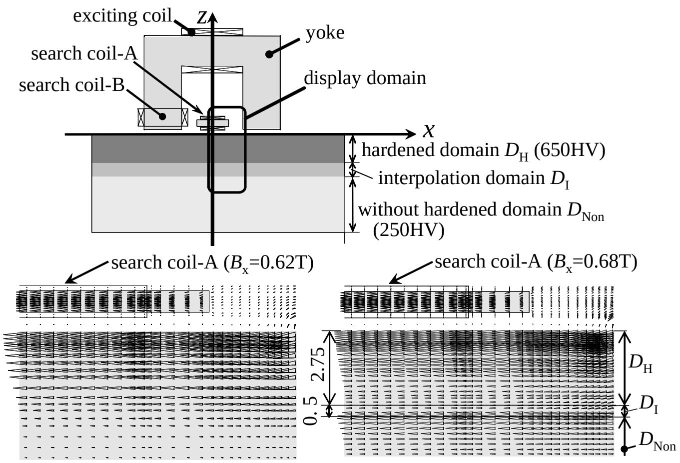


Fig.3. Example of hardness measured using Vickers hardness tester when the effective hardened depth is equal to 3mm.



(a) hardened depth is 0mm (B_{max} in the steel plate =1.52T)
(b) hardened depth is 3mm (B_{max} in the steel plate =1.24T)

Fig.4. Distribution of flux density in surface hardened steel plate (15Hz, 126AT).

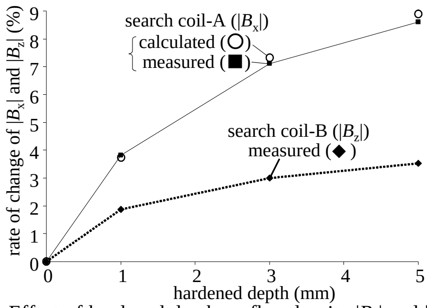


Fig.5. Effect of hardened depth on flux density $|B_x|$ and $|B_z|$ of the search coil-A and -B (15Hz, 126AT).

IV. Conclusions

The results obtained are summarized as follows:

(1) The permeability and conductivity of the layer with hardening in the surface hardened steel are lower than that of the layer without hardening.

(2) When the hardened depth is increased, the flux density inside surface hardened steel plate is decreased by the proposed inspection method, but the leakage flux of the surface of the steel plate is increased. This is, because the permeability and conductivity are decreased in the hardened layer.

(3) The inspection sensitivity of the detecting of the leakage flux on surface hardened steel is higher than the detection of flux density inside the magnetic yoke when the hardened depth is increased.

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