Analysis of Electromagnetic Inspection Method of Opposite Side Carburizing Depth in Steel Plate Taking Account of Minor Loop

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Abstract — There is a need to inspect the opposite side of carburized layer in a heating furnace steel tube in an oil-refining plant. The conductivity of the layer with carburizing is larger than that of the layer without carburizing in the steel, and its permeability is smaller than that of the layer without carburizing. Then, the estimation of the opposite side carburized depth in the steel is possible by using the differences of these electromagnetic properties. In this paper, the electromagnetic inspection method using a dc magnetic field and a minute ac magnetic field is proposed. The behavior of flux in steel is examined using 3-D nonlinear FEM taking account of minor loops and eddy current. It is shown that the inspection of opposite side of carburized depth in the steel is possible by using the differential permeability of minor loop of which the position on the hysteresis loop is affected by the depth of carburized layer.

I. Introduction

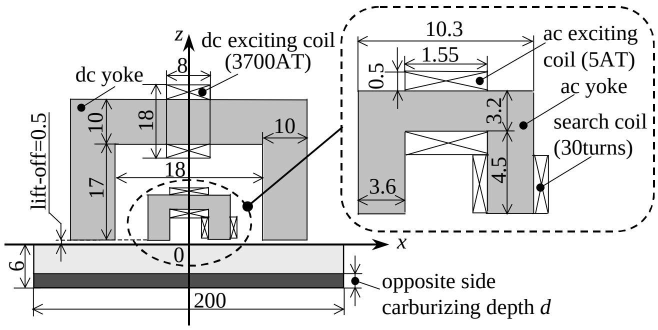
In the steel tube of a large-sized heating furnace in an oil-refining plant, its inner side is carburized. If the carburized depth is increased, the steel tube will be exploded suddenly and a big accident may occur. Therefore, the inspection of the carburized depth of inner side tube is important. The permeability and conductivity in the layer with and without the carburizing are different. Therefore, the evaluation of the carburizing depth is possible by detecting the difference of the electromagnetic characteristics.

In this paper, the electromagnetic inspection method of the opposite side carburizing depth is proposed. In this method, both dc magnetic field and an ac minute magnetic field are applied to the examined steel. The carburizing depth is obtained by evaluating the flux density in layers with and without opposite side carburized steel using the 3-D nonlinear FEM taking account of minor loops [1]. In addition, the experimental verification is also carried out.

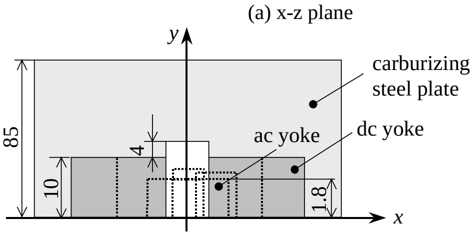
II. Inspection Model and Method of Analysis

Fig.1 shows the proposed model for inspecting the opposite side of the carburized depth in steel plate. This model is composed of the yokes for dc (static) and minute ac (alternating) magnetic field and a search coil. The distance (lift-off) between these yokes and the surface of steel plate is equal to 0.5mm. The dc and ac exciting ampere-turns are 3700AT and 5AT, respectively. The exciting frequency of the ac coil is 10kHz. Fig.2 shows the hysteresis curves with and without carburizing in steel. The conductivities with and without carburizing are 2.74×10^6 S/m and 7.51×10^6 S/m, respectively.

The flux density B in the steel plate with and without carburizing layer is produced by both dc and ac magnetic yokes. The magnetic field is analyzed using the 3-D edge-based hexahedral nonlinear FEM and the step-by-step method taking account of hysteresis (minor loop) and eddy current in



(a) x-z plane



(b) x-y plane

Fig.1. Inspection model of steel plate with outer side carburizing (1/2 domain).

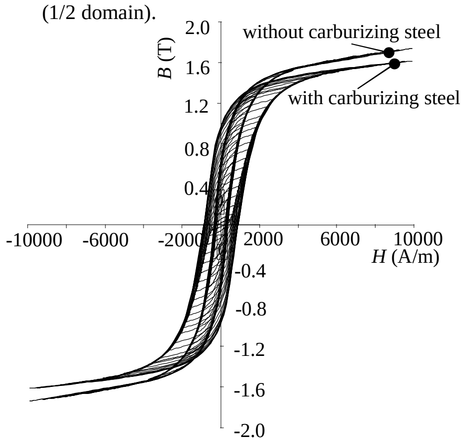


Fig.2. Hysteresis curves with and without carburizing in steel.

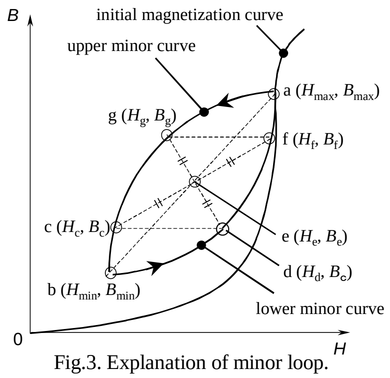


Fig.3. Explanation of minor loop.

the steel plate. The basic equation of eddy current analysis using the $\boldsymbol{A}$-ϕ method is given by:

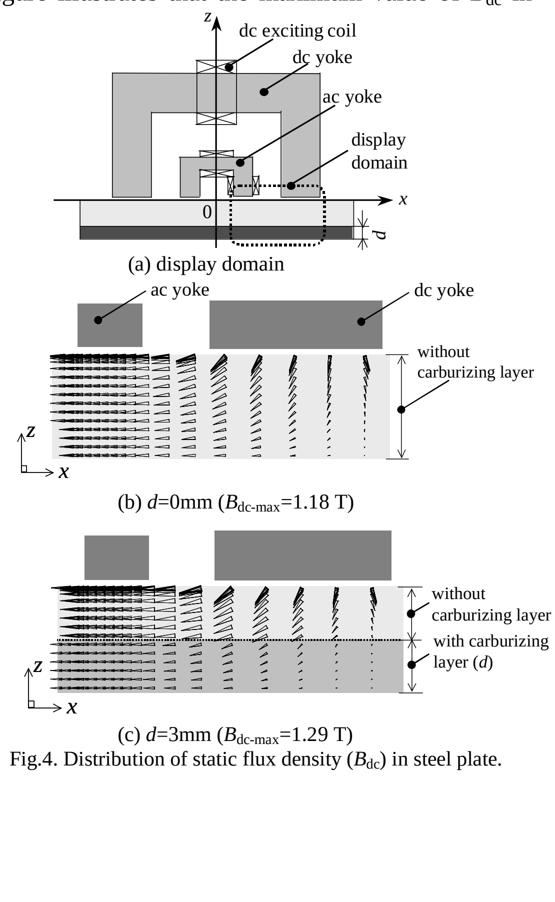
$$\boldsymbol{rot}(\nu \boldsymbol{rot A}) = \boldsymbol{J_o} - \sigma\left(\frac{\partial \boldsymbol{A}}{\partial \boldsymbol{t}} + \boldsymbol{grad}\phi\right) \quad (1)$$

$$\boldsymbol{div}\left\{-\sigma\left(\frac{\partial \boldsymbol{A}}{\partial \boldsymbol{t}} + \boldsymbol{grad}\phi\right)\right\} = 0 \quad (2)$$

where $\boldsymbol{A}$ is the magnetic vector potential, ϕ is the scalar potential, ν is the reluctivity, $\boldsymbol{J_o}$ is the current density and σ is the conductivity. The minor loop is modeled using hysteresis curves in Fig.2. It is assumed that the obtained B and H are at the point b (H_{min}, B_{min}) on the upper loop as shown in Fig.3. If the calculated flux density B_c at N-R iteration is larger than B_{min}, then B_c should be located at the point d (H_d, B_c) on the lower minor loop [1].

III. Electromagnetic Inspection of Opposite Side of Carburized Depth in Steel Plate

Fig.4 shows the distribution of only dc flux density (B_{dc}) in steel plate with and without opposite side carburizing depth (d). The figure illustrates that the maximum value of B_{dc} in steel plate is increased when d is increased. This is, because the B_{dc} is mostly distributed in the high permeability layer without carburizing in steel plate.



(a) display domain
(b) d=0mm ($B_{dc\text{-}max}$=1.18 T)
(c) d=3mm ($B_{dc\text{-}max}$=1.29 T)
Fig.4. Distribution of static flux density (B_{dc}) in steel plate.

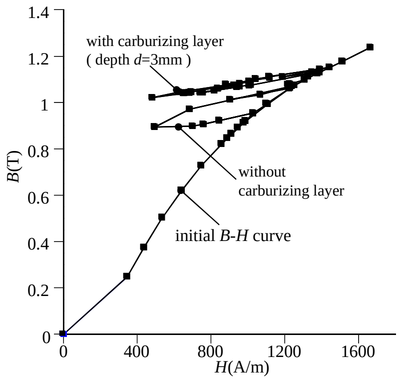


Fig.5. Effect of opposite side carburizing layer on minor loop (calculated).

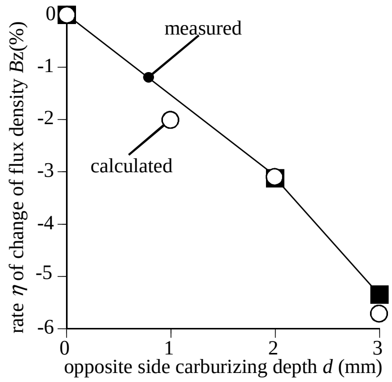


Fig.6. Effect of opposite side carburizing depth d on Bz in a search coil (calculated, dc=3700AT, ac=10kHz, 5AT).

Fig.5 shows the calculated result of minor loop at a surface point in the steel plate with and without opposite side carburizing layer (d=3mm). The figure indicates that the dc flux density in surface steel plate is increased when there exists the opposite side carburizing layer in steel plate. Therefore, a minor loop with low differential permeability is generated at the high flux density on the initial magnetization curve when the carburizing layer exists.

Fig.6 shows the effect of d on the change of flux density $|B_z|$ in a search coil. The figure illustrates that the inspection of the depth d is possible using the proposed method, since $|B_z|$ is decreased when d is increased.

IV. Conclusions

It is possible to estimate the opposite side carburizing depth d in steel plate by the dc magnetic field and the minute ac magnetic field using the proposed inspection method. Moreover, the calculated results using the 3-D nonlinear FEM taking account of minor loops are in agreement with the measured values.

V. Reference

[1] Y.Gotoh, and N.Takahashi: "Evaluation of detecting method with ac and dc excitations of opposite side defect in steel using 3d non-linear FEM taking account of minor loop ", *IEEE Trans. Magn.*, vol.44, no.6., pp.1622-1625, 2008.