Evaluation of non-destructive inspection for carburization depth of both surface and opposite side on steel tube using 3D nonlinear FEM

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Abstract- In the steel tube of a heating furnace in an oil-refining plant, its both surface and opposite side is carburized. If these carburization depths are increased, the steel tube will be exploded suddenly and a big accident may occur. Therefore, the inspection of these carburization depths is important. The conductivity of the layer with carburization is larger than the layer without carburization in the steel, and its permeability is smaller than the layer without carburization. Therefore, the estimation of both carburization depths is possible by using the differences of these electromagnetic properties. In this paper, the new technique of measuring the both depths by using two kinds of alternating magnetic field is proposed. The both depths are obtained by evaluating the flux density in layers with and without carburization steel tube using the 3-D nonlinear FEM. It is shown that the inspection of both depths is possible by using the differential electromagnetic characteristics.

***Index Terms*— Electromagnetic non-destructive inspection, carburization steel tube, both surface and opposite side depth, 3-D nonlinear finite element method**

I. Introduction

In recent years, the necessity for inspection of the deteriorated oil-refining plant in Japan is increased. In particular, the non-destructive inspection of a heating furnace steel tube in the plant is important. In the steel tube, its both surface and opposite side are carburized. If these carburization depths are increased, the steel tube will be exploded suddenly and a big accident may occur. Therefore, the inspection for these depths is important. The conductivity of the layer with carburization is larger than the layer without carburization in the steel tube, and its permeability is smaller than the layer without carburization [1]. Then, the evaluation of these depths is possible by detecting the difference of these electromagnetic characteristics [2-4].

In this paper, the electromagnetic inspection method for these carburization depths is proposed. In this method, the alternating magnetic field of the two kinds of exciting frequency using one sensor is applied to the examined steel tube. These both depths are obtained by evaluating the flux density in layers with and without carburization inside steel tube using the 3-D nonlinear FEM. In addition, the experimental verification is also carried out.

II. Inspection Model and Method of Analysis

A. Model and Analysis Method

Fig.1 shows the proposed model for inspecting the both surface and opposite side of the carburization depth in steel tube. This sensor is composed of the yokes (lamination of silicon steel plates) for alternating magnetic field and a search coil. As for the search coil, the z-direction flux density (B_z) on the surface of the steel tube is detected. The distance (lift-off : L_o) between the sensor and the surface of steel tube is equal to 0.5mm. The exciting frequency of 500Hz and 15Hz is used. The outer diameter and thickness of the steel tube (STFA26) are 115mm and 6mm, respectively. Fig.2 shows *B-H* curves [5] of the steel tube with and without carburization layer. The carbon concentration in the carburization layer is equal to 3.8%. The figure denotes that the permeability in the steel tube is decreased by the carburization. The conductivity of the steel with and without carburization is measured using the Kelvin bridge circuit. The conductivities of the steel tube with and without carburization are 2.45×10^6 S/m and 1.91×10^6 S/m, respectively. The conductivity in the steel tube

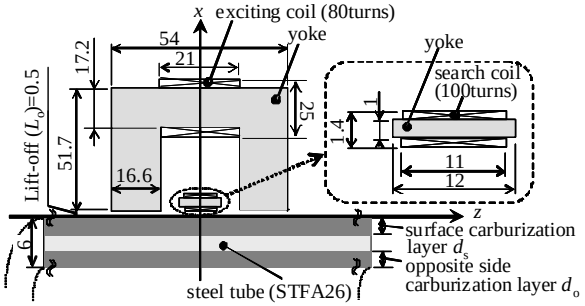

Fig.1. Proposed model for inspecting carburization depth of both the surface (d_s) and the opposite side (d_o) in steel tube.(unit : mm)

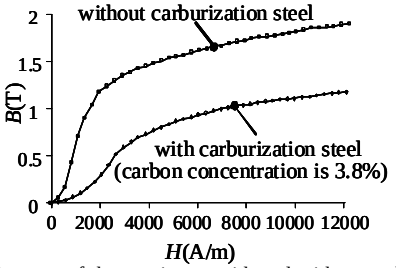

Fig.2. *B-H* curves of the specimens with and without carburization steel (STFA26 steel).

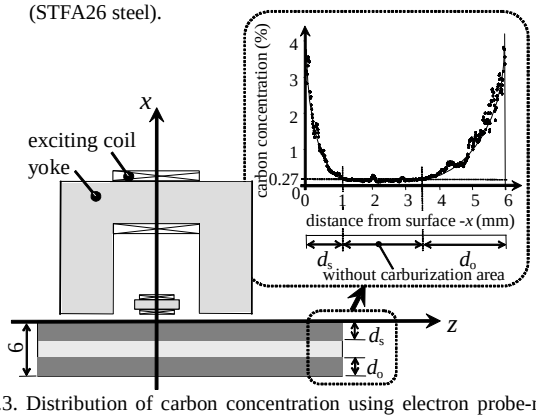

Fig.3. Distribution of carbon concentration using electron probe-micro analysis (EPMA) when d_s and d_o are equal to 1mm and 2.5mm.

is increased with the carburization. Fig.3 shows the example of measurement result of carbon concentration inside steel tube using electron probe-micro analysis (EPMA) when the surface carburization depth d_s and the opposite side depth d_o are equal to 1mm and 2.5mm, respectively. The domain that the carbon concentration is more than 0.27% is defined as the carburization layer. The figure denotes that the carbon concentration in the carburization layer is nonlinearly distributed from about 3.8% to 0.27% (layer without carburization). In the 3-D nonlinear FEM, the *B-H* curve of the carburization layer is obtained by the nonlinear interpolation as shown in Fig.3 using the *B-H* curves with and without carburization steel as shown in Fig.2. Moreover, the conductivity of the carburization layer is also similarly obtained by the nonlinear interpolation.

In this research, the carburizations depths of both d_s and d_o are inspected by the difference of these electromagnetic characteristics using two kinds of exchange magnetic fields. The proposed inspection process is as follows:

B. Inspection of Surface Carburization Depth

Fig.4 shows the effect of the change of flux density B_z in a search coil by the 3-D nonlinear FEM when only d_s is changed. The exciting conditions are 500Hz and 24AT, respectively. The figure denotes the rate of change from the measured value B_z of the steel tube without the carburization. The figure illustrates that B_z is increased when d_s is increased. This is because, the leakage flux between the magnetic yokes of the sensor is increased when d_s is increased, since the permeability of carburization layer is lower than the non-carburization layer. The d_s is inspected using the high exciting frequency of 500Hz.

C. Inspection of Opposite Side Carburization Depth

Fig.5 shows the effect of change B_z in a search coil by the 3-D nonlinear FEM when only d_o is changed. The exciting conditions are 15Hz and 16AT, respectively. The figure denotes the rate of change from the measured value B_z of the steel tube without the carburization. Moreover, the rate of flux density B_z for each d_o is also shown when each d_s is in constant depth. The d_o is inspected using this figure, since d_s was inspected using Fig.4.

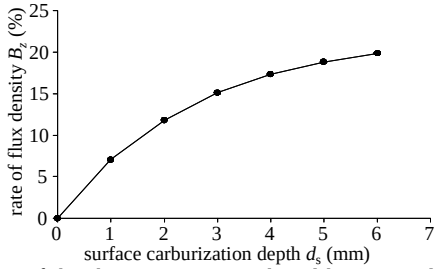

Fig.4. Effect of the change B_z in a search coil by 3-D nonlinear FEM when only the surface depth d_s is changed (500Hz, 16AT, calculated).

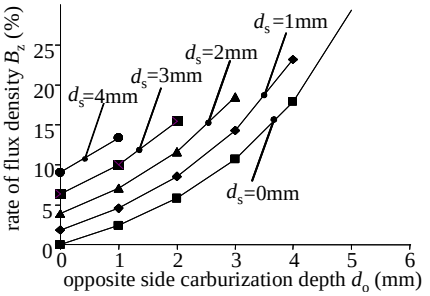

Fig.5. Effect of change B_z in a search coil by 3-D nonlinear FEM when only the opposite side depth d_o is changed (15Hz, 16AT, calculated).

TABLE I
OBTAINED RESULTS OF THE CARBURIZATION DEPTH OF BOTH THE SURFACE AND THE OPPOSITE IN ACTUAL HEATING FURNACE STEEL TUBE

depth side	actual depth (mm)	inspected depth (mm)	error(mm)
surface (d_s)	0.91	1	0.09
opposite (d_o)	0.64	0.63	0.01
surface (d_s)	1	0.99	0.01
opposite (d_o)	1.87	1.86	0.01
surface (d_s)	0.96	0.95	0.01
opposite (d_o)	1.5	1.55	0.05
surface (d_s)	1.16	1.06	0.1
opposite (d_o)	1.72	1.6	0.12
surface (d_s)	1.45	1.5	0.05
opposite (d_o)	1.91	2.07	0.16

III. INSPECTION RESULT OF ACTUAL CARBURIZATION STEEL

Table I shows the result of the estimated the both d_s and d_o inside the actual heating furnace steel tube by using the Fig.4 and Fig.5. These d_s and d_o are inspected by the proposed sensor. In the proposed method, these carburization depths are searched by the linear interpolation of the calculated values as shown in Fig.4 and 5. This table denotes that these carburization depths are in agreement with the obtained ones.

IV. CONCLUSIONS

The results obtained by this research are summarized as follows:

(1) The permeability in the heating furnace steel tube is decreased by the carburization. And, the conductivity of the steel tube is increased with the carburization.

(2) It is possible to estimate the carburization depth of both the surface d_s and the opposite side d_o in the actual heating furnace steel tube by the two kinds of exciting frequency using one proposed inspection sensor.

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