Magnetic NDE for Material Deterioration and Sub-mm Size Defect in Steel

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***Abstract*— This paper investigates a possibility of nondestructive evaluation of material deterioration and of detecting sub-mm sized small defect simultaneously using magnetic methods. Firstly, an assessment of both deterioration in steel and of small defect using one single-yoke probe was confirmed by a classical FEM simulation. Then the experimental verification was performed. The hysteresis loop measurement was sensitive to deterioration in material and scanning flux distribution was effective for detection of sub-mm sized defect. The deterioration and small defect can be also evaluated separately by a single measurement configuration.**

***Index Terms*— Nondestructive testing, Hysteresis, Magnetic flux leakage, Microstructure.**

I. Introduction

There exists a strong demand for nondestructive evaluation (NDE) of degradation in structural constructions to keep their integrity for long-term operations. Ferromagnetic steels are employed for those constructions and their degradation depends on alternations in microstructure of steels. Since magnetization process of steels correlates with their microstructure variations [1–3], a testing technique using magnetism is one of prospective candidates for such NDE.

Several magnetic methods like hysteresis loop, Barkhausen noise have been applied for characterizing materials [4] and for evaluation of residual stress [5], while magnetic flux leakage (MFL) method is used for detecting wall thinning on pipe in larger power plants [6]. In practical applications, an ultrasonic testing (UT), and an eddy current testing (ECT) are often adopted to inspect small defects in constructions, however, those method are not suitable for monitoring material deterioration before crack initiations. On the other hand, although magnetic testing have not used for detecting small defects because UT and ECT are effective tools for such objective, magnetic testing has the advantage in detection of deterioration in steels compared with UT and ECT and also has a potential to detect small defects using MFL method. Almost magnetic testing uses a magnetic yoke for magnetizing a specimen, which indicates evaluation of material deterioration and detection of small defects in materials can be possible simultaneously using a same measurement configuration. Thus, this paper discusses a capability of simultaneous evaluation of deterioration in materials and of sub-mm sized defect on materials separately using magnetic measurements.

II. Simulation By FEM Analysis

In order to confirm a feasibility of evaluating material deterioration and small (sub-mm size) defect on specimens simultaneously, a classical two-dimensional finite element method (FEM) analysis was adopted. Fig. 1 shows the analysis model, including dimensions of a single-yoke and a specimen. The Fe–Si steel was used for the single-yoke, and undeformed and deformed steels were used for the specimens. The virgin curves obtained by measurements using a ring-shaped sample for Fe–Si and a frame-shaped for steels were used for the calculations. The difference of deterioration in material was given as the variety in virgin curves of the specimens. The Φ–I curves and the distribution of magnetic flux density on the surface of specimens were calculated for both undeformed and deformed specimens with or without small defect, respectively. The defect is a hole with 100-1000 μm width and 100-700 μm depth.

Fig. 2 shows the initial Φ–I curves with variations in deterioration of specimen, as calculated by the FEM simulation when the specimens has a defect or not (defect size: 100 μm width, 500 μm depth). Significant difference appears between the results for undeformed and for deformed specimen while there is a slight variance between the results with defect and without defect. The loops for deformed specimen lean to the horizontal axis due to the decrease of permeability. These indicate the measurement of magnetization curves is sensitive to deterioration in material but is insensitive to small defects detection.

Fig. 3 shows the calculated distribution of leakage magnetic flux density of *x*- and *z*-component, B_x, B_z, when the single-yoke scans over the specimen with defects (The value of B_x, B_z is calculated at the center of yoke and at the surface of specimen). The prominent variation occurs in the distribution of leakage flux around defects. The *x*-component B_x has a peak at the center part of defect and *z*-component B_z, takes positive and negative peaks at the edge of defect. These show the potential of detection of sub-mm sized defects in steel. On the contrary, we confirmed that leakage flux density for specimens without defect are constant against position regardless of undeformed and deformed: the result means MFL method is ineffective against assessment of deterioration in material.

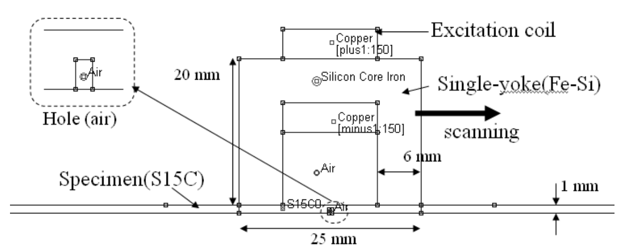

Fig. 1. Analysis model for FEM simulation.

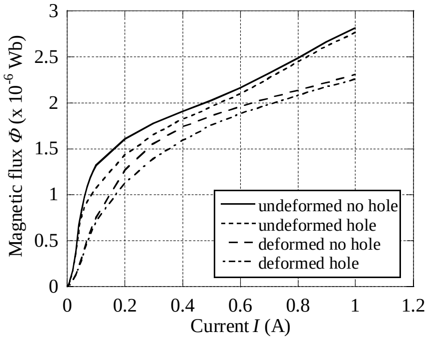

Fig. 2. Φ–*I* virgin curves simulated by FEM analysis.

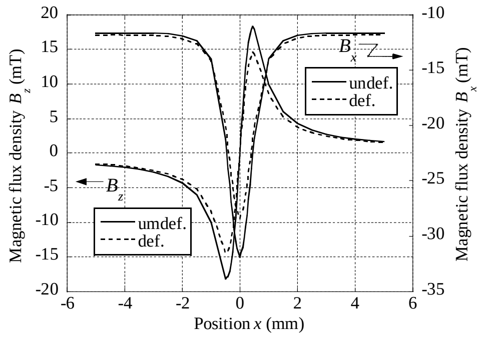

Fig. 3. Distributions of leakage magnetic flux density of *x*- and *z*-component simulated by FEM for specimen with a defect.

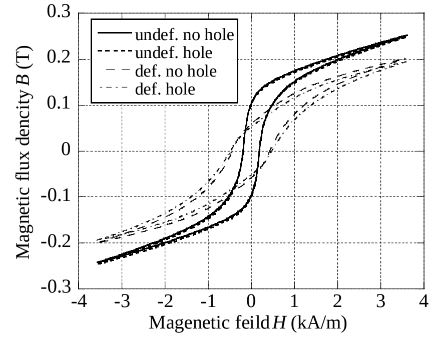

Fig. 4. Measured *B*–*H* hysteresis loops.

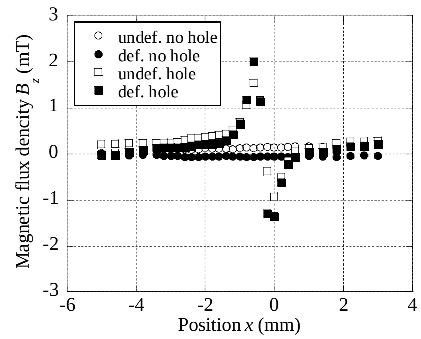

Fig. 5. Distributions of leakage magnetic flux density of *z*-component.

III. Experimental Procedure

The experimental setup was the same system as the model described in previous section. The magnetic flux through a magnetic circuit was measured by a pick-up coil on the yoke leg, and a magnetic field on the specimen surface was detected by a hall sensor with small active area. Low carbon steels (S15C), have dimension of 10 mm width, 55 mm length, and 1 mm thick, were used for the specimens. Several plates were deformed by cold rolling, and a hole was prepared to imitate sub-mm sized defect. The diameter of hole is 500 μm, and its depth is 500 μm. The *B*–*H* hysteresis loop was employed for evaluation of material deterioration on the experimental, although virgin curves were used in the simulation.

IV. Results And Discussion

Fig. 4 shows the measured *B*-*H* hysteresis loops for the plates undeformed/deformed and with/without a hole. The loops for the specimens with deformation incline to the filed axis compared with that for undeformed, and the coercive force is larger than that of undeformed. These results reflect the increase of dislocations, i.e. the variation in microstructure due to cold rolling. There are no or slightly variations between the specimens with/without hole.

Fig. 5 represents the distribution of leakage flux density of *z*-component, B_z, for the plates undeformed/deformed and with/without hole. The leakage flux is constant against position *x* for the plates without hole, even if those magnetic properties have changed. As to the results for the plates with a hole, magnetic flux shows the same tendency as the simulations, that is, it has peaks at the edge of hole, whereas no apparent differences reveal on the distribution of flux whether the plate is deformed or not.

The obtained results show that hysteresis measurement can detect deterioration in material while it is unfit to detection of small defects, and that assessment of flux distribution is sensitive to not degradation but small defects. The both measurement can be performed using the same measurement configuration, thus it was clear that evaluation of material deterioration and small defect simultaneously and independently using one single-yoke measurement. In practical cases, deterioration in material may be evaluated using coercivity/permeability on hysteresis loop, and defects are sized based on profiles of filed distribution. Additionally, a FEM simulation plays an important role in probe design and evaluating a magnetic property of a specimen itself from obtained results by magnetic measurement using a single-yoke configuration.

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