Highly sensitive magnetic nondestructive testing using magnetoresistive sensor for diagnosis of steel structures

K. Tsukada
Okayama University, Okayama 700-8530, Japan

To ensure the safety of civil infrastructures, simple and accurate inspection methods have been in high demand. Many types of nondestructive testing (NDT) methods are used in the diagnosis of steel structures. Corrosion and cracks often occur in steel structures, and ultrasonic testing (UT) is usually applied. Compared with UT, magnetic NDT such as eddy current testing (ECT) is limited to surface testing. Recently, we developed highly sensitive magnetic NDT using magnetic sensors to detect defects not only on the surface but also in deep regions of steel. By using an extremely low-frequency operation and highly sensitive magnetic sensors instead of pickup coils, we could also detect magnetic signals from deep regions. In the case of UT, surface treatment such as paint or rust stripping is necessary to obtain acoustic matching contact. By contrast, magnetic NDT is not affected by these types of interference materials. Based on this advantage, we developed an extremely low-frequency eddy current (ELECT) system using an anisotropic MR sensor to detect the reduction in thickness due to both surface and inner corrosion. In general, magnetic measurements for steel are difficult because of the high permeability of the material and the variations in their residual magnetization as compared with nonmagnetic material such as aluminum. To solve this problem, magnetic spectroscopy analysis was developed to achieve precise thickness measurements. The steel thickness of severely corroded steel structures of a dam and bridge, to which UT could not be applied, were successfully measured by the ELECT system. Related to the corrosion of steel structures is the collapse of lighting and road marker poles as a result of corrosion in underground locations, which has become a social problem as it sometimes results in major traffic accidents. To detect steel corrosion in hidden parts by soil or concrete, an integrated sensor probe consisting of two tilted magnetic sensors was developed. Results of field testing show that 1-mm thinning was successfully detected even at a depth of 50 mm. Furthermore, the magnetic results measured from the ground surface correlated well with directly measured results after ground digging operations were performed. As another defect of steel structures, cracks must be detected at an early stage. Cracks sometimes occur in welded parts and can be very difficult to detect. To detect cracks in these complicated parts, we developed two types of magnetic NDT systems. One is an unsaturated AC magnetic flux leakage (USAC-MFL) testing method that uses a gradiometer with AMR to detect inner cracks, and the other involves a small ECT probe that employs tunneling MR for use with complicated structures. The USAC-MFL is used to inspect inner and surface cracks in welded parts of rail. The small ECT probe is used to inspect surface cracks in welded angles such as U-shaped ribs used in steel decks of expressway bridges.

Reference
1) K. Tsukada, et al., IEEE Trans. Magn., 52 (2016) 6201504
2) K. Tsukada, et al., IEEE Trans. Magn., 53 (2017) 2501305
3) K. Tsukada, et al., IEEE Trans. Magn., 54(2018) 6202104
4) K. Tsukada, et al., IEEE Trans. Magn., 54(2018) 202205

Fig. 1 Inspection of underground corrosion at a road marker pole.

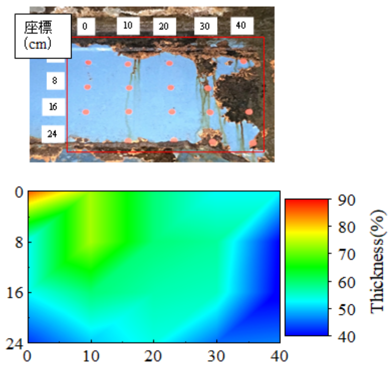

Fig. 2 Multipoint measurement of thickness reduction of bridge.

Development of a new nondestructive inspection method for concrete bridges

K. Maruyama[1], H. Morita[1], Y. Hashimoto[2]
[1]Konica Minolta, Inc, Tokyo 108-0075, Japan
[2]Konica Minolta Business Associates Co., LTD. Tokyo, 192−8505 Japan

Aging transportation infrastructures has become a social issue. Almost 50 years have passed since many road bridges and railroad bridges were constructed during the high economic growth period in Japan, while 50 years is said to be the expected lifetime of bridges. Some prestressed concrete bridges built during that time have deterioration in steel inside concrete due to insufficient grout filling and salt damage. However, it is not possible to degrade the internal steel by the usual visual inspection

We have developed a nondestructive inspection method that can detect the breakage of internal steel as one of the means to grasp the deterioration condition of a prestressed concrete bridge. By detecting internal steel breakage, it is possible to improve the quality of the prestressed concrete bridge's inspection, and we believe that this can lead to diagnosis of residual performance.

We named the developed method "Magnetic Stream Method". In this method, a special magnet is applied to the internal steel material from the outside of concrete, and a magnetic field is run from one direction, thereby capturing the sudden attenuation phenomenon of the magnetic field due to breakage. If there is no breakage in the internal steel, the magnetic force flows in a fixed direction while gradually weakening in proportion to the distance, so the magnetic force detected by the sensors also gradually decreases, but if there is a breakage, the flow of the magnetic force is stopped because of being divided, the magnetic force drops sharply at the divided portion.

Here is an experiment of measurement results using a post tension method prestressed concrete bridge model installed in our laboratory. The steel material to be measured is a standard type sheath tube with an inner diameter of 45 mm and a thickness of 0.27 mm, and a PC steel material (1S28.6) consisting of 19 strands with a diameter of 28.6 mm. As shown in Figure 1, when a two-component model in which sound steels and broken steels are arranged 20 cm apart is installed and measured, the sensor immediately above the broken steels can catch the rapid damping of the magnetic force as shown in Figure. 2.

Currently, the technology to analyze the data of "Magnetic Stream Method" on the cloud has been improved, and while conducting demonstration experiments with stakeholders and inspections on actual bridges, we always confirm customer value and usage scenes, and we are developing this technology as a nondestructive inspection solution combining magnetic sensing and IoT.

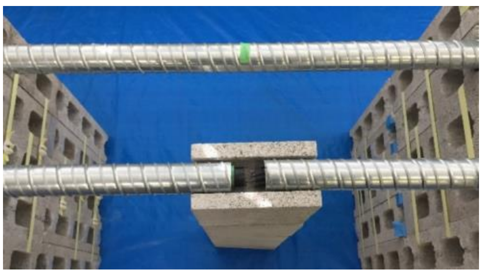

Figure 1 Model for experiment

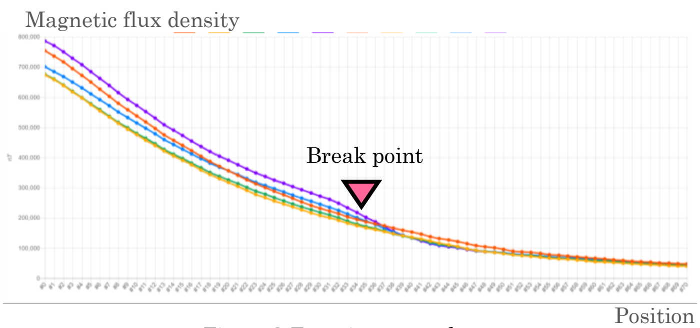

Figure 2 Experiment result

Failure analysis with magnetic field microscopy

Yuji Terui, Kazuhiro Suzuki, Masayoshi Tsutsumi, Norio Nishikawa, and Takehiro Nagatsuka
(Toshiba Nanoanalysis Corporation)

We, recently, see many consumer electrical products, which include smartphones, electric vehicles and drones, around the globe. Consumers have been demanding electric products with various functions and applications and long-lasting batteries, and manufacturers have been developing electrical products attracting more and more consumers. Such electric products have various semiconductor devices including power field effect transistors and lithium ion batteries.

Not just those products but also failure analysis technique has been making progress. We are likely to confront failure while developing or mass-producing things and we have to scrutinize it. When physical part of them has a problem, we, first, have to locate a defect. Generally speaking, the methods to locate such defects fall into two categories: a destructive method and a non-destructive method. For example, seeing the outside of a sample is the latter and seeing the inside of a sample after cutting it is the former. The non-destructive method is supposed to be performed before the destructive method. Non-destructive methods include X-ray computed tomography (X-ray CT) and magnetic field microscopy (MFM). X-ray CT is very useful in seeing the inside of a sample in three dimensions, which will provide insight into how things such defects within the sample look. MFM visualizes magnetic field intensities across a sample with a magnetic sensor. A superconducting quantum interference device (SQUID), a giant magneto resistance (GMR) sensor, a tunnel magneto resistance (TMR) sensor, and magneto-optical frequency mapping (MOFM) have been used for magnetic field imaging [1, 2, 3, 4]. Data analysis is also important, and some magnetic field analysis techniques have been introduced [1, 3]. When it comes to locating short circuits, it is really important to have a clear magnetic field intensity image. To do that, an electromagnetic field reconstruction method can be used, which calculate subsurface magnetic fields [3]. Using this method, we can obtain the intensity distribution of magnetic fields that are closer to the electric current that creates magnetic fields in distance than the positions where some of the magnetic fields are measured with a magnetic sensor.

In this study, we used a magnetic field microscope that we bought from Integral Geometry Science Inc. The microscope had a TMR sensor and an MI (magneto impedance) sensor. We also used a three-dimensional X-ray microscope, Xradia 520 Versa (Carl ZEISS X-ray microscopy Inc.).

We visualized the path of an electric current flowing through a power metal-oxide-semiconductor field effect transistor device. We, then, made a short circuit between the gate and the source in a power MOS-FET and succeeded in locating it from a magnetic field image. Another example is a ball grid array package with a short circuit between two solder bumps. After locating the short, we put the sample through the X-ray computed tomography scanner and clearly visualized the short circuit in three dimensions. We will talk about more details and other examples such as locating short circuits in lithium ion battery cells in the presentation.

References

1) Antonio Orozco, Florencia Rusli, Christopher Rowlett, Bernice Zee, Wen Qiu, J.M. Chin, and Fang-Jie Foo, “3D Fault Isolation in 2.5D Device comprising High Bandwidth Memory (HBM) Stacks and Processor Unit Using 3D Magnetic Field Imaging”, Conference Proceedings from the 42nd International Symposium for Testing and Failure Analysis, pp.426-432, 2016.
2) J. Gauderstad, F. Rusli, and T. Dean, “Magnetic Current Imaging and Photon Emission for Die Level Electrical Fault Isolation”, pp.245-248, 2015.
3) Yuki Mima, Kenjiro Kimura, Takashi Inao, Noriaki Oyabu, and Noriaki Kimura, “Failure analysis of electric circuit board by high resolution magnetic field microscopy”, CPMT Symposium Japan (ICSJ), 2013 IEEE 3rd. IEEE, pp. 1-4, 2013.
4) T. Nakamura, “Magnetic Current Imaging with MOFM: Magneto-Optical Frequency Mapping, and the applications for LSI Failure Analysis”, Proceedings of the 35th Annual NANO Testing Symposiu, pp.249-254, 2015.

Monitoring of structures and material characterization of steel using electromagnetic nondestructive evaluation method

Hiroaki Kikuchi
(Faculty of Science and Engineering, Iwate University)

Fundamental structural constructions such as bridges, highways and power generation plants are typically used for long term period after their constructions, and not easy to replace them frequently. However, a degradation and decrepit of structures progress during long term operation which may cause a failure of structures. Meanwhile, steel companies require the detection of nonmagnetic inclusions and defects during steel fabrication to enhance the reliability of their steel products for structural components. In both cases, inspection must be conducted nondestructively. Most of steels include iron and they therefore exhibit ferromagnetic property which indicates a potential of nondestructive evaluation using magnetic measurement. The ferromagnetic properties of materials are characterized by a magnetization hysteresis loop, and its magnetization process results from magnetic domain wall motions and magnetization rotations. Several parameters, coercivity, initial permeability, Barkhausen noise, defined on the magnetic measurements are used for evaluation (See Fig. 1). Since lattice defects like dislocations, precipitations and grain boundaries have interactions with domain wall motions and magnetization rotations[1)], the magnetic hysteresis loop is subjected to changes in the microstructures. On the other hand, degradations and mechanical properties of steels also depend on the microstructures, which means degradations and mechanical properties of steel have good correlation with the magnetic properties (See Fig. 2). As to detection of small inclusions or defects in steels, companies aim to detect defects less than 50 μm. Recent progress in development of a magnetic field sensor offers high sensitive and miniaturised sensor[3)], which enable us to detect small sized defects in steel by the magnetic flux leakage method. In our experiments, defect with up to 30 μm can be detected using a commercialized magnetic field sensor. Example of detection small defects using high sensitive GMI and GMR sensor will be introduced in the presentation.

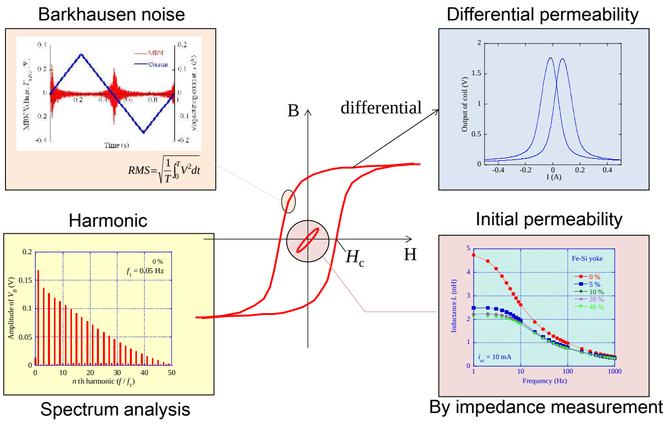

Fig. 1 Parameters for magnetic measurements.

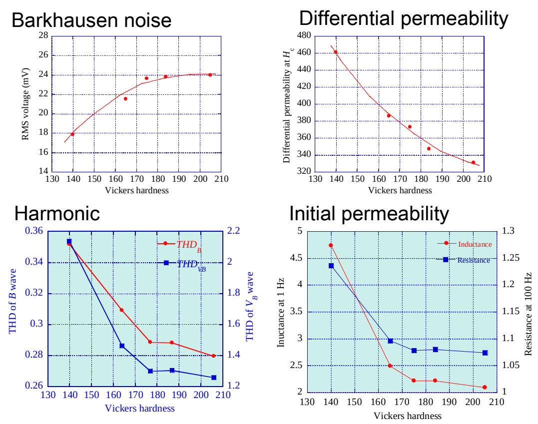

Fig. 2 Relations between hardness and magnetic parameters.

References

1) H. Kronmüller, *Int. J. Nondestruct. Testing*, **3**, pp.315-350 (1972).
2) G. Dobmann, *Electromagn. Nondestruct. Eval.* (XI), **31**, pp. 18-25 (2008).
3) H. Kikuchi, *IEEJ Trans. Fund. Mater.*, **137**, pp. 470-475 (2017).

Non-destructive inspection using acoustically stimulated electromagnetic method

Yuhei Suzuki[1,2], Hisato Yamada[2], Kenji Ikushima[2]
[1]IHI Inspection & Instrumentation Co., Ltd., Yokohama, 236-0004, Japan
[2]Department of Applied Physics, Tokyo University of A & T, Koganei, 184-8588, Japan

Many steel materials exhibit hysteresis in the variation of magnetic flux density ***B*** with respect to magnetic field ***H***. Because the hysteresis curve contains a number of independent parameters that is sensitive to factors such as stress, strain, grain size and heat treatment, they have been used in the determination of material properties in nondestructive evaluation (NDE). Although ultrasound waves can propagate through optically opaque substances, the majority of existing ultrasound techniques are restricted to determining the mechanical properties from the elasticity or mass density of a target. Recently, however, magnetic properties have been successfully measured and visualized by ultrasonic excitation[1-4)]. The principle of this technique is based on the generation of acoustically stimulated electromagnetic (ASEM) fields through magnetomechanical coupling. In the ASEM method, the spatial resolution of magnetic imaging is determined by ultrasound focusing, not limited to the size of magnetic sensors or the distance between the sensor and an object (lift-off).

The ASEM measurement setup is shown in Fig. 1(a). An ultrasound transducer with an acoustic delay line is used for avoiding the EM noise generated by the transducer. A specimen is subjected in external magnetic fields ***H*** which is applied by a commercial electromagnetic coil. The ASEM signal emitted from a specimen is picked up through a resonant loop antenna tuned to the ultrasound frequency.

We measured magnetic hysteresis curves and visualized the magnetic-flux distribution in a steel plate[3)]. The monotonous ASEM intensity over the scanned area is observed in a defect-free plate (Fig.1(b)), while a clear contrast of the ASEM intensity is widely observed in the plate with a defect (Fig.1(c)). This result indicates that a magnification effect due to magnetic flux distribution. We should note that the minimum detectable size of defects is not limited to the size of the ultrasonic focal spot due to the magnification effect, which is beneficial for NDE. Magnetic-flux probing by ultrasonic waves is thus expected to be a viable method of nondestructive material inspection.

Figure 2 represents the stress dependence of local hysteresis loop measured by the ASEM method. The hysteresis loop changes clearly under tensile stress, indicating that local hysteresis quantities such as coercivity will be a promising parameter as an index of quantitative evaluation of stress.

References
1) K. Ikushima *et al*., Appl. Phys. Lett. 89, 194103 (2006). 2) H. Yamada *et al.,* Rev. Sci. Instrum. **84**, 044903 (2013).
3) H. Yamada *et al*., Jpn. J. Appl. Phys. **54**, 086601 (2015). 4) H. Yamada *et al.,* Jpn. J. Appl. Phys. **57**, 07LB09 (2018).

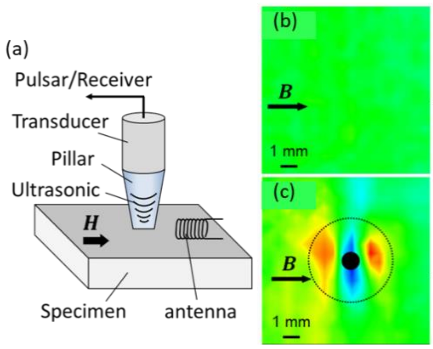

Fig. 1 (a) Measurement setup and ASEM image for a steel plate (b) without and (c) with an artificial defect.

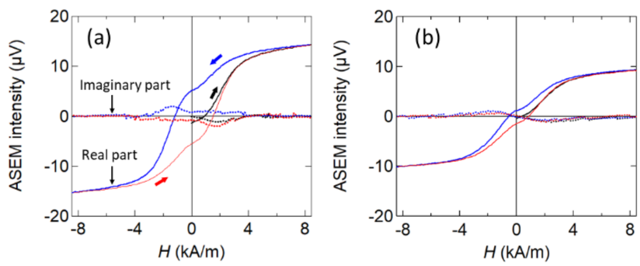

Fig. 2 Stress dependence of the ASEM hysteresis loop at (a) 0 MPa and (b) 333 MPa.

Low invasive high-frequency field measurement system using magneto-optical effect

Kazushi Ishiyama
(Research Institute of Electrical Communication, Tohoku University)

Measuring magnetic near field is one of the key technologies against the problem of the electromagnetic interference (EMI). However the previous methods generally use metal probes and cables. Therefore the accuracy of the system is poor by the many unexpected couplings between the metals and the measuring magnetic fields [1]. Measurements that use the magneto-optical effect can overcome this problem. The magneto-optical measurements do not use any metallic materials and cables, therefore it has very small invasivness for the magnetic fields. To achieve a high resolution, a stroboscopic method that employs short laser pulses are utilized. To improve the sensitivity, a new modulation system was carried out. Two waveforms having same frequency and different phase are used for modulate the pulsed laser. By switching the waveforms, modulated signal can obtained. Therefore the measured signal can be enlarged using the Lock-in amplifier. As a result, the proposed system can visualized RF magnetic near-field around IC chips.

In the previous works for magneto-optical measurement system [2], the magnetic field have to be burst modulated in order to obtain high sensitivity. However, this is not suitable for real circuit. To overcome this problem, we propose a new modulation schemes that do not require the modulation of the circuit current. That is obtained by a BPSK (Binary Phase-Shift Keying) modulation method. In this method, two signals of same frequency and different phase are switched by the SPDT (Single-Pole Double-Throw), and the generated signal is used as an external input trigger of the laser. As a result, the pulsed laser oscillates while periodically switching in two phase groups. The measuring circuit was shown in Fig.1. By applying these modulation schemes, the detection sensitivity of 0.1mOe (peak to peak) was realized up to 6GHz. Figure 2 shows the measured result of field distribution around an amplifier chip. The measuring condition is as follows; RF input: 1GHz, 10dBm, burst modulation 7.5kHz, measured area: 5x5 mm, 100x100 points. The strong magnetic field was observed at the output port. It is confirmed that the system is suitable for detecting the point to be shielded for EMI.

References
1) M. Takahashi, H. Ota, K. I. Arai and R. Sato: "Magnetic Near-Field Distribution Measurement above a Patch Antenna by Using an Optical Waveguide Probe", IEICE Trans. Commun., E88-B, pp. 3140-3145 (2005).
2) H. Nasuno, S. Hashi, K. Ishiyama, "Stroboscopic technique for measuring magnetic-field waveforms utilizing magneto-optical effect", IEEE Trans. Magn., vol. 47, pp.4011-4013 (2011).

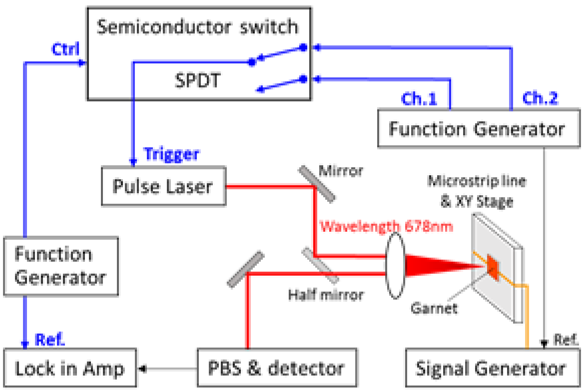

Fig.1 Measuring circuit of the new modulation system

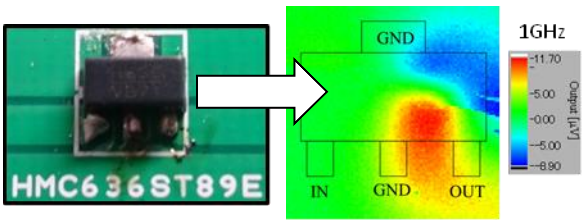

Fig.2 Field distribution around amplifier chip.