Regular Paper

Fatigue Evaluation of Low Carbon Steel by Means of the Inductance Method Using a Pancake-Type Coil

Mohachiro OKA [*1](Mem.), Terutoshi YAKUSHIJI [*1], Yuji. TSUCHIDA [*2](Mem.) and Masato. ENOKIZONO [*2](Mem.)

In recent years, low carbon steel has been utilized in many structural components that are used in our everyday surroundings. If external force is repeatedly applied to these parts made of low carbon steel over the span of many years, fatigue accumulates in these components. There is a possibility that these structural components may even be destroyed when excessive fatigue accumulates. Therefore, it is important to know the amount of fatigue damage that will be accumulated in these components in order to prevent the component from destruction. We are researching the Eddy Current Testing (ECT) Method to evaluate fatigue damage in these components made of low carbon steel. In general, the ECT method uses a high excitation frequency of 100 kHz or more to enlarge the eddy current generated in a specimen. However, the eddy current generated by the ECT sensor concentrates only on the surface of a specimen, as a result of the skin effect. If a high excitation frequency is used, the ETC method obtains only information regarding fatigue damage at the surface of a specimen. Thus, we apply a non-destructive fatigue evaluation for low carbon steel using the inductance method composed of a pancake-type coil that can use a low excitation frequency of about 10 kHz. In this case, the skin depth is about 0.18 mm. If this excitation frequency is used, the amount of fatigue damage in low carbon steel can be measured irrespective of corrosion and defect on the surface of a specimen. There is a good correlation between the amount of fatigue damage and the inductance of the pancake-type coil. This paper describes the fatigue evaluation method for low carbon steel using an inductance method.

Keywords: fatigue, low carbon steel, pancake-type coil, inductance method, LCR meter.
(*Received: 11 October 2011, Revised: 26 February 2012, 25 April 2012, Accepted: 17 May 2012*)

1. Introduction

Recently, steel has been used in a lot of the structural components that are employed in our surroundings. As for long term use of these structural components, the material is known to deteriorate due to fatigue and corrosion. Because deterioration of these structural components might cause an accident, this is a big problem. Thus, it is necessary to prevent any accident that originates in the material deterioration of the structural components. Active researches are being conducted all over the world for the detection of small cracks in structural components that create the possibility of causing an accident. However, there is the possibility of an accident happening after a short time even if the crack is small. It is necessary to know the fatigue situation of the structural component before the crack happens in order to prevent the accident. If we can know about the deterioration ahead of time, the accident can be prevented by the replacement of a component.

The deterioration detection method has been researched by many domestic and foreign research laboratories; it has been an important topic of research in recent years. For instance, magnetism and the microstructure of the material are closely related. Thus, the attempt to evaluate the material deterioration from the change in the Barkhausen noise and the minor loop of the *B-H* curve are performed in magnetic materials such as steel [1, 2, 3]. In such a research situation, our group has researched in which deterioration in stainless steels is evaluated by the residual magnetization method and the ECT method [4, 5, 6, 7]. The eddy current method is applied to the fatigue evaluation and it attains good results in the detection of the plane bending fatigue. However, these fatigue evaluation methods still contain some problems. One of problems of the eddy current method is not appreciable of fatigue of the inside of the specimen. The cause is a skin effect. In the plane bending fatigue, fatigue concentrates on the specimen's surface. However, fatigue doesn't concentrate on the surface in the partially pulsating fatigue. In particular, it is important to know fatigue of the inside of specimen to prevent the accident caused by fatigue. To know fatigue of the inside of the specimen by the eddy current method, a lower excitation frequency is necessary.

Conversely, because strength is high and the price is cheap, low carbon steel is widely used in many fields, such as in homes and industry. It is very important to evaluate the amount of fatigue damage accumulated to parts made of low carbon steel. In order to evaluate the amount of fatigue damage in low carbon steel, the eddy current method was applied. Thus, we apply a non-destructive fatigue evaluation method for low carbon steel using the inductance method composed of a pancake-type coil that can use a low excitation frequency of about 10 kHz. This paper describes the non-destructive fatigue evaluation method for low carbon steel using the inductance method.

Correspondence: M. OKA, Oita National College of Technology, 1666 Maki, Oita 870-0152, Japan
email: oka@oita-ct.ac.jp
[*1] Oita National College of Technology [*2] Oita University

2. Principle of the Inductance Method

2.1 The Principle of the Inductance Method

Fig. 1 shows the principle of the inductance method that used a pancake-type coil. When a pancake-type coil is excited by an alternate current, an eddy current ($\boldsymbol{J}_e$) is induced in a specimen, such as is shown in Fig. 1. In this case, a displacement current can be neglected. Then, the eddy current can be written as Eq. (1), where μ and ρ are magnetic permeability and resistivity of a specimen respectively. Eq. (1) contains μ and ρ of a specimen. Therefore, an eddy current in a specimen changes when electromagnetic properties such as μ and ρ of a specimen changes by fatigue. An inductance (L) of a pancake-type coil is influenced by the change of μ and ρ. If L can be measured, we can know the fatigue damage of a specimen. If ρ of the specimen becomes large when the specimen and the coil are at the position of Fig. 1, L of the pancake-type coil grows. Similarly, if μ of the specimen grows, L increases. Moreover, the inductance of the pancake-type coil decreases if μ and ρ become small, respectively.

$$\nabla^2 \boldsymbol{J}_e = \frac{\mu}{\rho}\frac{\partial \boldsymbol{J}_e}{\partial t}. \qquad (1)$$

2.2 The Pancake-Type Coil

Fig. 2 shows the size of the pancake-type coil used in our experiments. The pancake-type coil is a sensor for the inductance method. Fig. 3 shows the photograph of the pancake-type coil that is a same shape pancake-type coil used in the experiment. The number of turns in the pancake-type coil and the diameter of copper wire were 369 turns and 0.04 mm respectively. The outer diameter, the inner diameter, and the height of the pancake-type coil were 5.04 mm, 1.80 mm, and 0.5 mm respectively as shown in Fig. 2. The inductance of the pancake-type coil (L) was 413.8 μH when it was in air and the excitation frequency (f_{ex}) was 10 kHz.

3. Specimen and Experiment

3.1 The Specimen

The specimen used in our experiments was made of low carbon steel. Fig. 4 shows the dimensions of a specimen and the position of the measurement area. The thickness of the specimen was about 1.0 mm. To exclude residual stress by mechanical processing, specimens were cut in the shape shown in Fig. 4 by the electrical discharge machining method. Table 1 shows the chemical composition of the specimen used in our experiments. Tensile strength of this specimen was about 280 MPa at 30 °C. In order to avoid the influence of temperature effect, the experiments were performed at room temperature.

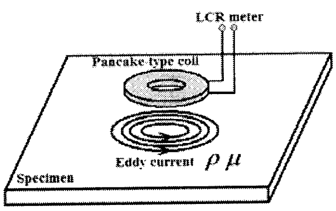

Fig. 1. The principle of the inductance method using the pancake-type coil.

3.2 The Measurement System

Fig. 5 shows the block diagram of a measurement system for the inductance method. The pancake-type coil constants such as L and θ were measured by a LCR meter (ZM2353, NF Corporation). L is inductance of the pancake-type coil, and θ is a phase angle of the impedance of the pancake-type coil. They were inputted

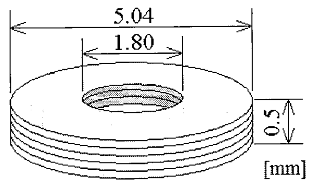

Fig. 2. The pancake-type coil used in our experiments.

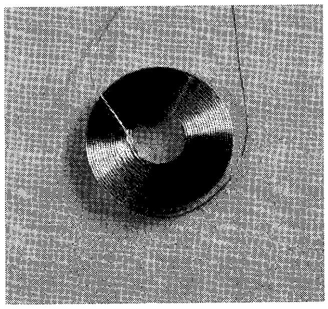

Fig. 3. The photograph of the pancake-type coil.

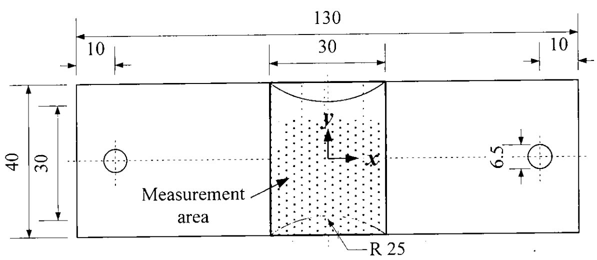

Fig. 4. The dimension of a specimen (t=1 mm) and arrangement of the measurement area (Unit=mm).

Table 1 The chemical composition of low carbon. steel (*wt*%).

C	Si	Mn	P	S	S-Al
0.05	0.01	0.21	0.015	0.009	0.047

into a control computer by using the GP-IB interface. The measurement was repeated twice at the same measurement point. Measured values of L and θ were a mean value of the measurement result of two times. To avoid the influence of a stray capacitance and a mutual inductance among four cables that connected between the LCR meter and the pancake-type coil, the zero point of a LCR meter was adjusted before the measurement using the correction function of the LCR meter. The 4-terminal method was used to obtain accurate L and θ. When the excitation frequency 10 kHz and the specimen made of low carbon steel were used, the skin depth was about 0.18 mm. In this case, μ_r (relative permeability) and ρ of the specimen were 100 and 1.25×10^{-7} Ωm, respectively. If this excitation frequency had been used, the amount of fatigue damage in low carbon steel could be measured irrespective of corrosion and the defect on the surface of the specimen. Measuring the amount of fatigue damage by this inductance method is important.

3.3 The Experimental Method

To make a clear relationship among the amount of fatigue damage, L and θ, experiments were carefully carried out in the procedure shown in Fig. 6. First, L and θ were measured by using the LCR meter within the measurement area of 30 mm x 40 mm every 1 mm step as shown in Fig. 4. The measurement area was a part of the net multiplication of Fig. 4. In our experiments, the excitation frequency and the excitation voltage were 10 kHz and 1 V_{rms}, respectively. The lift-off, which is the distance between the specimen and the lower side of the pancake-type coil, was about 0.05 mm. Then, we measured L and θ on a specimen in 1271 points. Next, the partially pulsating stress was applied by the tensile and compression tester (V-0674, SAGINOMIYA SEISAKUSHO) which operated at 20 Hz. The maximum tensile force of this tester was about ±49 kN, and the maximum displacement amplitude of it was 30 mm. This procedure was repeated until the specimen was destroyed. The following experiments were executed when the stress ratio (R) was 0.1. In this case, a stress waveform was a sinusoidal wave. Fig. 7 shows the photograph of a specimen set in the tensile and compression tester. This experiment was a fatigue test that impressed the partially pulsating stress to the specimen.

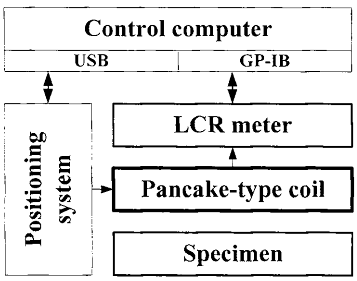

Fig. 5. The block diagram of a measurement system used in these experiments.

3.4 S-N Curve of the Specimen (low carbon steel)

In order to know the fatigue limit of our specimen, we measured the relationship between the partially pulsating stress (σ_a) and the number of stress cycles (N) (S-N curve). This relationship is shown in Fig. 8. When σ_a is 90 MPa, the specimen did not break until 1.0×10^7 cycles. From this result, the fatigue limit of low carbon steel used in our experiments was estimated to be 90 MPa. An impressed partially pulsating stress (σ_a) of the following experiments was decided using this S-N curve such as 120 MPa, 125 MPa, and 130 MPa.

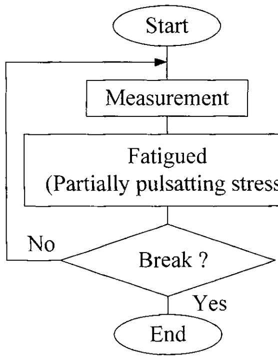

Fig. 6. Experimental procedure.

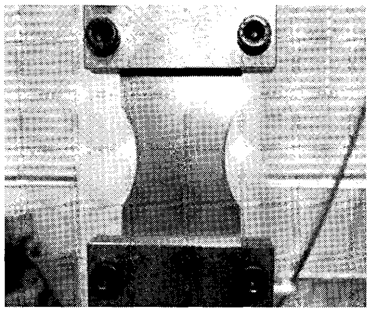

Fig. 7. Photograph of a specimen set in the tensile and compression tester.

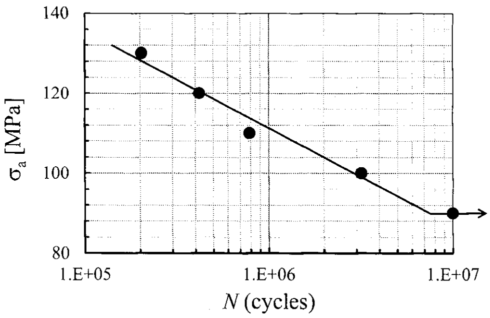

Fig. 8. The relationship between the partially pulsating stress (σ_a) and number of stress cycles (N) (S-N curve).

4. Experimental Results and Discussions

4.1 The Distribution of L

Fig. 9 shows the distribution of L at each measurement position when the partially pulsating stress amplitude (σ_a) and the number of stress cycles (N) were zero, respectively. Because this specimen had not become fatigued, the distribution of L was smooth. There is a decrease in L in the vicinity of x = 0 mm and y = 15 mm because of the shape of the specimen. Fig. 10 shows L at each position when σ_a and N are 130 MPa and 200000 respectively. In this figure, the decrease in L in the vicinity of x = 0 mm and y = ±15 mm was large because this specimen was fatigued.

Fig. 1 shows the same relationship as Fig. 10. In this case, the L axis of this figure had expanded about 10 times compared with the L axis of Fig. 10. L decreased according to the distribution of the amount of fatigue damage. It is understood that the distribution of L shows the distribution of fatigue damage in low carbon steel. From Fig. 10 and Fig. 11, it is thought that L of the pancake-type coil had become small, because ρ and μ of the specimen changed by fatigue.

In Fig. 11, it is well known that the partially pulsating stress concentrates on the part of a circular notch of the midrange of the specimen. The micro-defect such as the dislocation increases in this part of the specimen for fatigue by the partially pulsating stress. These defects cause an increase in ρ and the decrease in μ. On the other hand, when ρ of the specimen increases, L of the pancake-type coil that is adjacent to the specimen grows. Similarly, when μ decreases, it becomes small. Therefore, it seems that a decrease in μ of the specimen caused by fatigue mainly contributes to the decrease in L of the pancake- type coil in this sample.

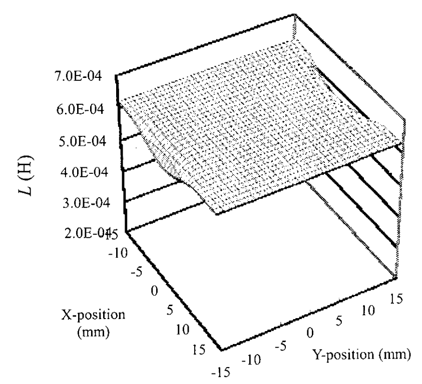

Fig. 9. The distribution of L of the pancake-type coil (N=0, f_{ex}=10 kHz).

4.2 The Distribution of θ

Fig. 12 shows θ at each position when σ_a and N are 130 MPa and 200000 respectively. In this case, θ axis has been expanded to 10 times as well as Fig. 11. In this figure, the decrease in θ in the vicinity of x = 0 mm and y=±15 mm was large because this specimen was fatigued.

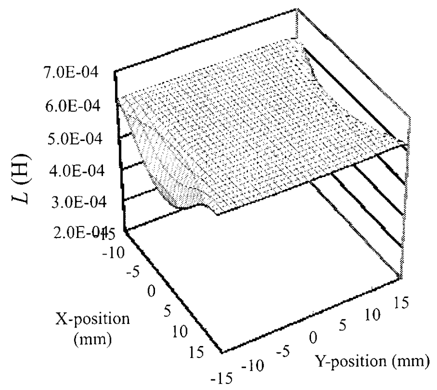

Fig. 10. The distribution of L of the pancake-type coil (N=200000, σ_a=130 MPa, f_{ex}=10 kHz).

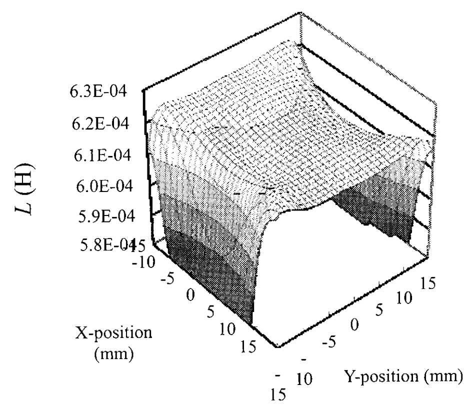

Fig. 11. The distribution of L of the pancake-type coil (N=200000, σ_a=130 MPa, f_{ex}=10 kHz).

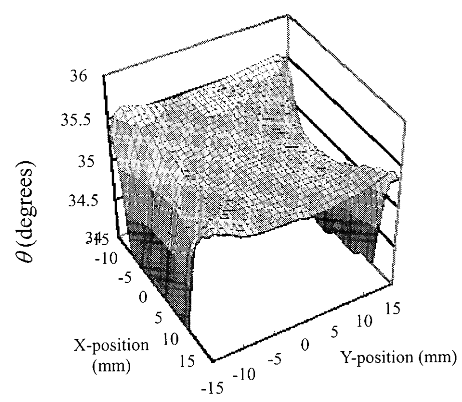

Fig. 12. The distribution of θ of the pancake-type coil (N=200000, σ_a=130 MPa, f_{ex}=10 kHz).

4.3 Shrinking of the Center Part of the Specimen

The specimen expanded when the tensile stress was impressed to the specimen. The width of the specimen shrunk, according to the Poisson ratio when the specimen expanded. Fig. 13 shows the relationship between the width of the center part of the specimen and the number of stress cycles. In this experiment, fatigue that accumulated in the specimen was measured by the change in the inductance of the pancake-type coil. The change in the width of the center part of this specimen influenced the evaluation value of the amount of fatigue damage.

The absolute difference ($|dL|$) was defined as follows. The value of $L_{\min}$ is the smallest value of L when the sensor is on the line of the y-axis of ±12 mm. In addition, L_0 is the mean value of L in the center part of a specimen for $N = 0$ was assumed to be an index of the fatigue accumulation. Consequently, the absolute difference ($|dL| = |L_0\text{-}L_{\min}|$) was defined as the parameter that evaluated fatigue in low carbon steel. The purpose of deciding the parameter $|dL|$ is to assume the relations between fatigue and $|dL|$ to be positive. $|d\theta|$ was defined as well as $|dL|$. Even if the width of the center part of the specimen had shrunk by fatigue by 3 mm, the change in L is about 8×10^{-6} H or less. Therefore, the influence of shrinking of the specimen to $|dL|$ and $|d\theta|$ used by this experiment as an index of fatigue can be disregarded.

4.4 Relationship among $|dL|$, N, and σ_a

Fig. 14 shows the relationship among $|dL|$, N, and σ_a. From this figure, $|dL|$ increases according to an increase under the partially pulsating stress. Moreover, $|dL|$ increases roughly according to an increase in N and σ_a. Fig. 15 shows the relationship among $|d\theta|$ N, and σ_a. From this figure, $|d\theta|$ increases according to an increase within N and σ_a. From these figures, $|dL|$ and $|d\theta|$ catch fatigue damage of low carbon steel and they depend on the amount of fatigue damage caused by the partially pulsating stress. On the other hand, in the case of 130 MPa (Circle), $|dL|$ and $|d\theta|$ seem to have changed into the N-type according to an increase under the partially pulsating stress. At present, the cause of this change is not understood. It will be necessary to discuss it in detail in the future. Consequently, it is thought that $|dL|$ and $|d\theta|$ are a kind of parameter for fatigue evaluation of low carbon steel. However, the change in inductance of the pancake-type coil by the fatigue of low carbon steel is very small, and the difference in measurements is somewhat large, too. It is thought that the change in L is small because the change in μ and ρ of low carbon steel by fatigue is small.

Fig. 16 shows the relationship among $|dL|$, N, and σ_a. From this figure, $|dL|$ roughly increases according to an increase within N and σ_a, when the partially pulsating stress is large when the excitation frequency is 100 kHz. In Fig. 16, the tendency to the change in $|dL|$ is almost the same as the case for 10 kHz the excitation frequency. Thus, even if the low excitation frequency such as 10 kHz was used, this method is appreciable of fatigue of low carbon steel.

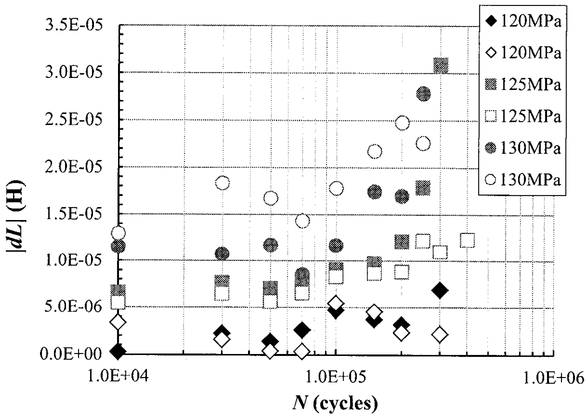

Fig. 14. The relationship among $|dL|$ of the pancake-type coil, σ_a, and N (f_{ex}=10 kHz).

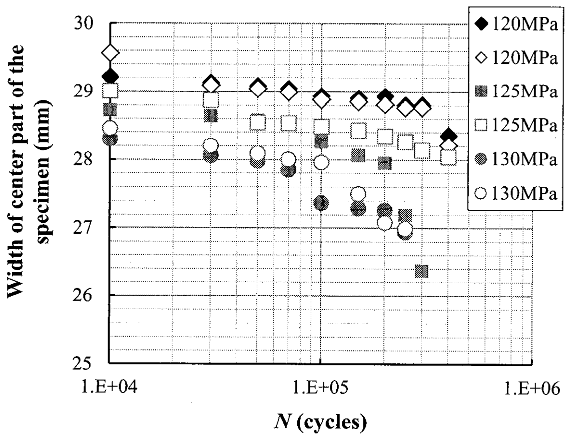

Fig. 13. The relationship between the width of the center of the part of the specimen and the number of stress cycles.

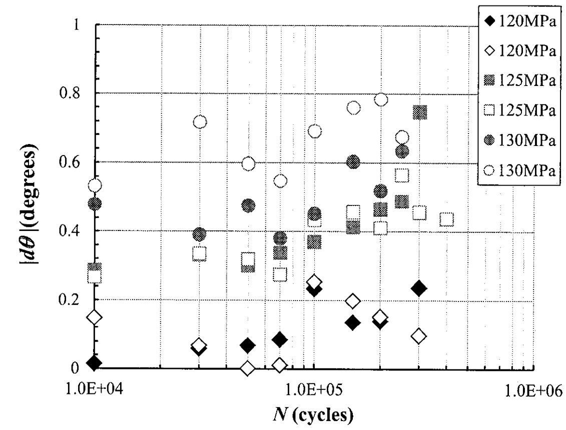

Fig. 15. The relationship among $|d\theta|$ of the pancake-type coil, σ_a, and N (f_{ex}=10 kHz).

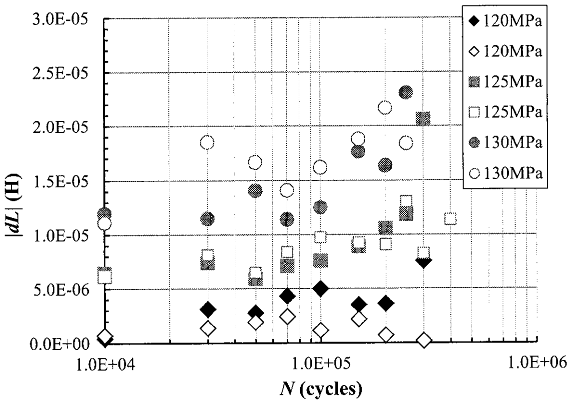

Fig. 16. The relationship among $|dL|$ of the pancake-type coil, σ_a, and N (f_{ex}=100 kHz).

5. Conclusion

In this paper, we applied the inductance method to the fatigue evaluation of low carbon steel. As a result, the correlation among the inductance of the pancake-type coil, the phase angle of the pancake-type coil impedance, and the amount of fatigue damage of low carbon steel was obtained. Moreover, when the partially pulsating stress is large, fatigue damage was obviously detected by this proposed method. The inductance method using a pancake-type coil is useful for the detection of fatigue damage in low carbon steel. The value of $|dL|$ and $|d\theta|$ depends on the partially pulsating stress and the number of stress cycles. However, the inductance method using the pancake-type coil shows that employing 10 kHz for the excitation frequency has a problem with a small fatigue detection signal and the measurement values vary somewhat. Consequently, to increase the accuracy of fatigue measurement, the improvement of the non-destructive evaluation system using magnetic methods is needed in the future.

Acknowledgment

This work was supported in part by the Japan Society for the Promotion of Science under Grant No. 23560518.

References

[1] M. Kaplan, C. H. Gur and M. Erdogam, "Characterization of dual-phase steels using magnetic Barkhausen noise technique," *J. Nondestructive Evaluation*, Vol. 26, PP. 79-87, 2007.

[2] H. Kikuchi, A. Takahashi, L. Zhang, K. Ara, Y. Kamada and S. Takahashi, "NDE for magnetic material by minor loop method using magnetic yoke probe," *Electromagnetic Nondestructive Evaluation (IX)*, IOS Press, pp. 119-125, 2005.

[3] Y. Nakasone, Y. Iwasaki, T. Shimizu and S. Kasumi; "Electromagnetic non-destructive detection of damage in an austenitic stainless steel by the use of martensitic transformation," *J. Jpn. Soc. Appl. Electromag. Mech..*, Vol. 9, No. 2, pp. 123-130, 2001.

[4] M. Oka, Y. Tsuchida, T. Yakushiji and M. Enokizono, "Fatigue evaluation for a ferritic stainless steel (SUS430) by the eddy current method using the pancake-type coil," *IEEE Tran. Magn.*, Vol. 46, No. 2, pp. 540-543, 2010.

[5] M. Oka, E. Wada, T. Yakushiji, Y. Tsuchida and M. Enokizono, "Evaluation of fatigue damage in SUS316 and SUS316L using the FG magnetic sensor," *Electromagnetic Nondestructive Evaluation (IX),* IOS Press, pp. 159-165, 2005.

[6] M. Oka, T. Yakushiji, S. Nagato, Y. Tsuchida and M. Enokizono, "Estimation of fatigue damage for an austenitic stainless steel (SUS304) using a pancake-type coil," *Review of Progress in Quantitative Nondestructive Evaluation*, American Institute of Physics, CP975, Vol. 27, pp. 1244-1251, 2008.

[7] T. Teramoto, S. Kitamura, A. Terasaki, T. Suzuki, Y. Miyazaki and M. Iwamatsu, "Material damage evaluation of carbon steel by ECT sensors", *Proc. 20th Symp. Electromag. Dyn.*, pp.37-40, 2008.