Fatigue Detection of Steel Plate
Using Magnetic Flux Leakage Method

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Abstract. Non-destructive evaluation of cracks in steel structures has been widely investigated and various types of evaluation method have been reported. However, a non-destructive evaluation system for fatigue which is an early stage of crack is limited. Therefore, a reliable and practical evaluation method of fatigue for steel plate is highly required. In this study, the fatigue in a steel plate was evaluated by measuring a leaked magnetic field caused by permeability change of fatigue. To detect a leaked magnetic field from a measurement sample, AC magnetic field was applied above the steel plate to the direction parallel to the sample surface using ferrite yoke with induction coils. To avoid the skin effect and ensure the magnetic field penetrating inside the sample, magnetic field of low frequency range was applied. The leaked magnetic field was measured by a magneto-resistive (MR) sensor and a magnetic field distribution was obtained by multipoint measurement using automatically controllable stage. The direction of measured field was three axes which is parallel or perpendicular to the applied magnetic field. As a measurement sample, a steel plate (SS 400) was bended using Schenck type fatigue testing machine. The stress amplitude was 294 N/mm², the cycle was 30 Hz, and the test time was 1 and 4 h. To investigate the material characteristic change before and after fatigue test, the B-H curve and residual stress of each steel plate were measured.

The measured B-H curve indicated that the permeability of steel plate decreased when the stress by the fatigue test was applied. Therefore, it was confirmed that the magnetic characteristic of the steel plate changed after fatigue test. Because of this change, the leaked magnetic field depended on the fatigue testing time and the intensity of leaked magnetic field increased with increasing the fatigue testing time. These results suggest that the fatigue area in a steel plate can be estimated using magnetic method and a practical non-destructive evaluation system for fatigue detection is expected.

Introduction

Steel plate is one of the important materials in our society and it is widely used for structures, such as a building, bridge, ship and so on. In these structures, the degradation of steel plate is becoming an important issue. Generally, a crack and reduction of steel plate in thickness are observed when the steel plate was used for a long time and degraded. To detect a crack and thickness reduction, many types of non-destructive evaluation method have been proposed. However, these methods deal with the state that the degradation progressed to a certain extent. On the other hand, the early stage detection of degradation in a steel plate which has no crack...
and thickness reduction is highly desirable. Although a fatigue detection method and an estimation of fatigue have been also reported [1-4], a practical evaluation method suitable for the fatigue in a steel plate has not been established.

In this study, to detect a fatigue in a steel plate by a magnetic method, the magnetic property change of the steel plate after fatigue test investigated and the correlation between the magnetic property change caused by fatigue in a steel plate and the magnetic field distribution measured by a magnetic flux leakage method was discussed. In addition, the residual stress was also measured for the steel plate before and after fatigue test to confirm the internal structure change of the steel plate.

**Measurement system and experimental conditions**

**Automatic measurement system using a magnetic flux leakage method**

The developed system is based on a magnetic flux leakage method and consists of a measurement probe, an automatically controllable x-y stage, a function generator, a current source and a lock-in amplifier. The measurement probe is composed of induction coils, a ferrite yoke, and a magneto-resistive (MR) sensor (Honeywell, HMC2003). The induction coils are wound at both ends of ferrite yoke (30 turns at each end) and the ferrite yoke and MR sensor are fixed on an acrylic plate which is connected to the x-y stage, as shown in Fig. 1. The use of ferrite yoke enables to apply magnetic field above the steel plate and this configuration suitable for a practical measurement. The measurement procedure of magnetic field distribution is as follows. A sinusoidal current of 1 A was applied to the induction coils and magnetic field of x-direction was applied to the steel plate. The frequency of applied magnetic field was 50 Hz to avoid the skin effect. The MR sensor can measure x-, y-, and z-axis component of magnetic field and the leaked magnetic fields of three axes were measured. The strength and phase of leaked magnetic field from a sample were detected by a lock-in amplifier. After detecting the magnetic signal, the measurement probe was moved by the x-y stage and multipoint measurement was performed by repeating the above procedure. The interval of measurement point was 2 mm.

*Fig. 1. Configuration of the developed magnetic flux leakage system.*
To obtain a magnetic signal related to the magnetic signal change caused by a sample, the imaginary part of measured magnetic field vector $B_s$ was used, of which phase was adjusted so that the magnetic field mapping represents the signal change caused by a sample [5, 6]. $B_s$ is given by the following equation.

$$B_s = |B_{\text{mea}}| \sin (\theta + \alpha)$$

(1)

Here, $|B_{\text{mea}}|$ and $\theta$ are the strength and phase of measured magnetic field, and $\alpha$ is arbitrary value for phase adjustment. In this study, $\alpha$ was set to $1/3 \pi$ because this $\alpha$ value showed a signal change derived from the sample.

Measurement sample and evaluation of material characteristics

A steel plate of SS 400 was used as a measurement sample and was processed to the shape for the fatigue test, as shown in Fig. 2. The thickness of steel plate is 10 mm. The processed steel plate was bended by a Schenck type fatigue testing machine. The stress amplitude and test speed was 294 N / mm$^2$ and 30 Hz, respectively. In this study, the samples of which test time is 1 and 4 h were prepared. The measured area of leaked magnetic field was 40 mm × 72 mm indicated by dotted line in Fig. 2. To investigate the magnetic property of the steel plate with fatigue, B-H curve was measured for the sample before and after fatigue. For the B-H curve measurement, the steel plate was cut using electrical discharge machining to avoid the generation of heat and stress which affect the magnetic property. Moreover, the residual stress of steel plate was measured at the center line of the sample (see Fig. 2) using X-ray residual stress analyzer. The direction of residual stress measured in this study is x- and y-direction, and the interval of measurement position was 10 mm.

Results and discussions

Leaked magnetic field distribution after fatigue test

The distribution mappings of leaked magnetic field $B_s$ for each sensitive axis direction were created and the mappings before and after fatigue test were compared (Figs. 3 and 4). In spite of the fatigue testing time and sensitive axis direction of detected field, the intensity of $B_s$ in each sensitive axis direction increased when the stress was applied to the steel plate by the
fatigue test. Moreover, the distributions of $B_s$ in each sensitive axis direction for the sample before fatigue test were almost the same, as shown in Figs. 3 and 4. This result indicates that the magnetic property of each steel plate before fatigue test was almost the same and the effect of sample processing on magnetic property did not occur. Therefore, the change of leaked magnetic field after fatigue test is estimated to be caused by the stress applied by the fatigue test.

However, the amount of change in $B_s$ depended on the sensitive axis direction and the change of $B_s$, of which direction is parallel to the applied magnetic field (sensitive x-axis direction), was large as seen in Figs. 3(a), 3(b), 4(a), and 4(b). This is because the leaked magnetic field intensity which is parallel to the applied magnetic field is large and the amount of change in the magnetic field of x-axis direction caused by fatigue test increased. When the fatigue testing time increased, the distribution of $B_s$ after fatigue test was different. This result is confirmed at the region of mapping where the intensity of $B_s$ showed high and low value (the red and blue area in each mapping became large after fatigue test). In particular, this phenomenon is obvious in the sensitive axis direction of z-axis, as seen in Fig. 4(f). Therefore, it was found that the change in magnetic property depends on the fatigue testing time although the amount of its change is lower than that occurs between before and after fatigue test. In addition, it is also found that the amount of change in the mapping between 1 and 4 h-fatigue testing times depended on the sensitive axis direction. For example, the difference between Fig. 3(f) and Fig. 4(f) is larger than that between Fig. 3(a) and Fig. 4(a). This implies that the magnetic response of the steel plate with fatigue is not isotropic. In

![Fig. 3. Leaked magnetic field distribution of each sensitive axis direction generated from the steel plate before and after fatigue test of 1 h.](image-url)
the next section, to clarify the reason for the leaked magnetic field change between before and after fatigue test, the correlation between the leaked magnetic field change and material property such as internal structure and magnetic property of steel plate is discussed.

**Fig. 4.** Leaked magnetic field distribution of each sensitive axis direction generated from the steel plate before and after fatigue test of 4 h.

**Fig. 5.** Residual stress of x- and y- direction for the steel plate before and after fatigue test.
Residual stress and magnetic characteristic after fatigue test

To confirm the internal structure change of the steel plate after fatigue test, the residual stress of steel plate before and after fatigue test was measured. The sample with the fatigue test of 4 h was used. Figures 5(a) and (b) shows the residual stress of x- and y-direction measured at the position shown by the black dots in Fig. 2. Although the residual stress between the samples before and after fatigue test depended on the measurement position, a tendency that the residual stress increases after fatigue test was observed in both directions. It was also observed that the amount of residual stress change at each measurement point showed similar tendency except for the measured position of −40 mm. These results indicate that the internal structure of steel plate changed owing to the stress applied by the fatigue test.

The B-H curves of the steel plate before and after fatigue test are shown in Fig. 6. As a sample with fatigue, the broken steel plate which had 4.8 h-fatigue test was used. When the stress was applied to the steel plate by fatigue test, the B-H curve was degraded indicating the decrease in permeability. Meanwhile, the steel plate before fatigue test showed sharp variation of B-H curve. The difference of B-H curve indicates that the magnetic property of steel plate changed when the stress was applied. This magnetic property change is also explained by the change of residual stress after fatigue test because the B-H curve changes depending on the residual stress in a steel plate [7]. Therefore, the leaked magnetic field change after fatigue test shown in Figs. 3 and 4 was caused by this magnetic property change. As seen in Figs. 3 and 4, the leaked magnetic field increased after fatigue test. To explain this phenomenon, the permeability of steel plate after fatigue test should decrease. As shown in Fig. 6, it is found from B-H curve that the permeability of steel plate decreased after fatigue test and this result can explain the increase in the leaked magnetic field after fatigue test. Therefore, it was clarified that the magnetic property changed because of internal structure change after fatigue test and this magnetic property change can be detected and visualize the fatigue area using a magnetic flux leakage method.

Conclusion

To investigate the correlation between the magnetic field distribution and the material property before and after fatigue test, the leaked magnetic field distributions for the steel plate before and after fatigue test were measured and these distributions were compared to the residual stress and B-H curves. When the stress was applied to the steel plate by a fatigue test, the leaked magnetic field increased and a remarkable change was observed when the
sensitive axis direction is the same as the applied magnetic field direction. The residual stress and B-H curve also changed owing to the stress applied by the fatigue test and these results indicated the decrease in the permeability of steel plate after fatigue test. This magnetic property change can explain the leaked magnetic field change before and after fatigue test and the field distribution measured by a magnetic flux leakage method is expected to be used for fatigue detection.

References