Fatigue Damage Evaluation of SUS304 Steel Using Magnetism Change in Fatigue Process

Daiki Shiozawa¹, Yoshikazu Nakai¹, Yoshitaka Ejima²

¹. Department of Mechanical Engineering, Kobe University, Kobe, Japan
². Graduate School of Engineering, Kobe University, Kobe, Japan

Abstract: For the detection of fatigue damage before crack initiation in an austenitic stainless steel, SUS304, we investigated the possibility of the fatigue damage detection and evaluation from the change in the magnetization. The changes in the magnetization before the fatigue crack initiation were observed in the fatigue process at several stress amplitude and stress ratio. It was found that the changes in the leakage magnetic flux density $B_z$ were observed before crack initiation and the location, where the maximum changes in the value of $B_z$ observed, coincided with the location of the stress concentration, where the crack was formed. The experimental results obtained by fatigue tests conducted under the stress ratio, $R$, of $-1$, and $0.1$ showed that the change in the magnetization of SUS304 specimen was depended on the stress ratio. Under either stress ratio, the value of $B_z$ rapidly increased just before crack initiation. When no crack was found, increasing rate of $B_z$ decreased with increasing the number of cycles, and the value of $B_z$ was saturated to a certain value. It was found that fatigue damage before crack initiation can be detected from the change in the magnetization in SUS304 steel.

Key words: Non-destructive testing method, Fatigue damage, SUS304 steels, Magnetic sensor, Martensitic transformation

1. INCLUSION

In recent years, the aging degradation of infrastructures, such as bridges, power plants and chemical plants under long-term service, has become a serious social problem. Then, the nondestructive damage monitoring, and health monitoring of infrastructures have gotten considerable attention [1].

Conventional nondestructive testing (NDT) methods such as the ultrasonic method, the radiation method and the electric potential method have been mainly applied to the detection of defects such as cracks and voids. When some defects are detected by NDT, the integrity of structures can be evaluated using fracture mechanics analysis. If the fatigue damage and mechanical degradation before crack initiation can be detected by NDT, it provides us very early signals of damage initiation before catastrophic failure of the structures, then, we can maintain the high reliability of structures at high level.

One of the parameters indicating the mechanical degradation is considered to be the change in the magnetization, such as the coercitivity, the initial permeability and Barkhausen noise. Several studies on the development of NDT using the change in the magnetization have been carried out. Takahashi et al. showed that the rate of the coercitivity to the magnetic susceptibility corresponds with applied stress [2].

NDT for austenitic stainless steel using the change in magnetization is scientific and practical interesting. Austenitic stainless steel is widely used in industry, such as structural components of nuclear power plants and chemical plants, for their superior mechanical and corrosion properties. Austenitic stainless steel is originally nonmagnetic, but it changed to be magnetic at room temperature caused by plasticity induced martensitic transformation. Nakasone et al. proposed a method to detect cracks using the leakage magnetic flux density caused by the martensitic transformation around crack tips in a nonmagnetic austenitic stainless steel at room temperature [3]. Nagae et al. investigated the relationship between the changes in the magnetization and damages those are attributed to plastic deformation, fatigue, and creep [4]. Although some correlations between magnetization and damage have been found, few quantitative relations between the magnetization and the fatigue damage have been reported.

Then, in the present study, detection of fatigue damage before crack initiation for austenitic stainless steel, SUS304, was studied. In this paper, we observed the change in the magnetization before the fatigue crack initiation at several stress amplitudes and stress ratios. The change in the magnetization was evaluated from the leakage magnetic flux density measured by MI (magneto-impedance) sensor. The possibility of the fatigue damage detection and evaluation using the change in the magnetization in SUS304 was investigated.

2. MATERIAL AND EXPERIMENTAL PROCEDURES

The material for this study was an austenitic stainless steel, JIS SUS304. The chemical composition of this steel (in mass%) was as follows: 0.04C, 0.42Si, 1.07Mn, 0.028P, 0.004S, 8.31Ni, 18.0Cr, and balance Fe. The 0.2% proof stress was 280 MPa, the tensile strength was 572 MPa, and the elongation was 55%.

The shape and dimensions of specimens are shown in Fig. 1, where (a) is a smooth specimen and (b) is a notched specimen for the observation of the change in...
magnetization in crack initiation process.

The surface of the specimens was polished using emery paper and electrochemically polished before conducting fatigue tests.

A computer-controlled electrodynamic testing machine was employed for the fatigue tests. Fully reversed cyclic bending moment ($R = -1$) with a frequency of 40 Hz was applied to the specimen.

A schematic illustration of the apparatus used in the measurement of the leakage magnetic flux density distribution is shown in Fig. 2. MI (magneto-impedance) sensor was used for measuring the leakage magnetic flux density of the specimen. The magnetic flux density can be measured by MI sensor with the resolution of 0.1 mG, which is $10^4$ times smaller than the value measured by the hall element used in industrial use. The magnetic sensing detection of MI sensor is $z$-axis, so that this measurement system provides us the $z$-component of the leakage magnetic flux density over the specimen. Output voltage signal from the MI sensor was measured through A/D converter in the personal computer.

The measurement points for type A specimen were set on grid points with a interval of 0.5 mm over a measured area of $9 \times 10$ mm. The conditions of measurement points for type B specimen are as follow; grid points interval: 0.25 mm, measured area: $3 \times 4$ mm.

Fatigue test was interrupted after every predetermined number of cycles, and the specimen was removed from the fatigue testing machine for the measurement of the magnetic flux density $B_z$ over the specimen. Before measuring the leakage magnetic flux density, specimens were magnetized by the permanent magnet with magnetic intensity of 4000 Gs, as shown in Fig. 3. Since the magnetic directions of generated martensitic phase are random under a natural condition, the measured change in the leakage magnetic flux density caused by the martensitic phase is small. The magnetic directions of the martensitic phase are conformed to be $z$-axis by the permanent magnet, and then $B_z$ over the specimen is large compared with that of the natural condition.

3. EXPERIMENTAL RESULTS

3.1 $S$-$N$ curve

Figure 4 indicates the relationship between the stress amplitude and the number of cycles to failure, $N_f$. The fatigue limit was 310 MPa for the stress ratio $R=-1$, and 220 MPa for $R=0.1$.

3.2 Type A specimen and stress ratio $R=-1$

The leakage magnetic flux density distributions measured in the fatigue process are shown in Fig. 5 at the nominal stress amplitude of 360 MPa. In Figure 5, the dotted lines indicate the position of the specimen set. The number of cycles to failure at this stress amplitude was $8.9 \times 10^4$ cycles. Figure 6 indicates the specimen surface observed by optical microscope.

It was found from Fig. 5(a) that the magnetic flux density values at the minimum cross-section area were smaller than remote values in the early stage of the fatigue process. The change in magnetic flux density depends on the magnetization direction. The leakage magnetic flux density on the surface, which contacted with the north pole of the permanent magnet, was shown in Fig. 5. The measured surface of the specimen acted as the south pole of a compound magnet. When the opposite surface was measured, magnetic flux density values at the part of minimum cross-section were larger than the remote value. This behavior of the change in the leakage magnetic flux density indicates the martensitic phases magnetized by the permanent magnet.
phase distributions using a vibrating sample magnetometer and a flux gate sensor [3].

In Figure 5(b), when the number of cycles, $N$, was $2.0 \times 10^7$, the magnetic flux densities distribution showed the local decrease and took minimum value at one of notch roots. By the optical microscope, however, no apparent indication of fatigue damage was observed at both notch roots, as shown in Fig. 6(a).

At $N = 3.5 \times 10^5$ cycles, a crack was found by the optical microscope in Fig. 6(b). It was found from Fig. 5(c) that the location of the crack initiation coincided with the location of the minimum value of the magnetic flux density.

In Figures, 5(d) and (e), after $N = 4.5 \times 10^5$ cycles, the minimum value of the leakage magnetic flux density, $B_z$, decreased with increasing the number of cycles. It was found from Figs. 5(d), (e), 6(c) and (d) that the values of $B_z$ near the center of the specimen also rapidly decreased to the minimum value with increasing crack length. The decreasing of the measured values near the center of the specimen occurred around the location of the crack tip.

In Figures, 5(b)–(e), the minimum value of $B_z$ was observed inside of the specimen. Since the spatial resolution is about 0.5mm×0.5mm, the MI sensor obtains the average value of $B_z$ at the area of the sensor’s spatial resolution. When the MI sensor is located just above the edge of the specimen, the sensor detects average value containing outside of the specimen. So the measured values inside of the specimen are larger than those just above the edge of specimen.

For investigating the change in the magnetization of SUS304 specimen before crack initiation, the change in minimum value of the leakage magnetic flux density, $\Delta B_z$, at nominal stress amplitude of 360MPa and 340MPa are shown in Figs. 7. The value of $\Delta B_z$ indicates the difference from the initial measured value before fatigue tests. The crack length was also plotted in Fig. 7 to investigate the effect of crack propagation on the change.
in the magnetization.

It was found from Fig. 7 that the change in the magnetic flux density, $\Delta B_z$, began before crack initiation in both cases. After crack initiation, the increasing rates of $\Delta B_z$ was large.

The change in the magnetization in the crack propagation process should come from the martensitic transformation induced by the stress concentration at the crack tip. On the other hand, the change in the magnetization before crack initiation is considered to reflect the plastic strain.

Fatigue tests were also carried out at a stress amplitude of 300 MPa, which was below the fatigue limit of the material at $R=1$. For this specimen, no crack was observed at $N=1.0 \times 10^5$ cycles.

The changes in the minimum value of the leakage magnetic flux density, $\Delta B_z$, are shown in Fig. 8. It was found that the change in the magnetization of specimen begins at the early stage in the fatigue process. After $N=2.0 \times 10^5$ cycles, the increasing rate of the magnetization is small. This behavior is considered to be the saturation of the martensitic phases caused by the martensitic transformation.

It was found from Figs 7 and 8 that the final value of the leakage magnetic flux density for $\sigma_a=300$ MPa was larger than that for $\sigma_a=360$ MPa and 340 MPa at the number of cycles to crack initiation. This result indicates that it is difficult to estimate the remaining life to crack initiation from the critical value of the leakage magnetic flux density. To evaluate the fatigue damage, increasing rate of the leakage flux density was investigated.

The increasing rate of the change in the minimum value of the magnetic flux density, $\Delta B_z$, was shown in Fig. 9. It was found that under $\sigma_a=360$MPa and 340MPa, the increasing rate of $\Delta B_z$ before the crack initiation was large compared with that for $\sigma_a=300$MPa. The increasing rate just after the crack initiation was larger than that in the early stage of the fatigue process. On the other hand, when the stress amplitude was below the fatigue limit, the increase rate of $\Delta B_z$ was smaller than that above the fatigue limit, and it decreased with increasing the number of cycles.

Therefore it is possible to predict whether the crack initiation occurs in the future and when crack will be initiated using the increasing rate of the magnetization.

### 3.3 Type B specimen and stress ratio $R = 0.1$

The fatigue tests were carried out at the stress ratio, $R$,
Fig. 10 Distribution of magnetic flux density at stress ratio $R$ of 0.1, stress amplitude $\sigma_t$ of 240MPa.

Fig. 11 Change in leakage magnetic flux density at the notch root for stress ratio $R$ of 0.1.

of 0.1. The leakage magnetic flux density distributions at the nominal stress amplitude $\sigma_t$ of 240MPa are shown in Fig. 10. In Figure 10, the dotted lines indicate the position of the specimen set. The number of cycles to failure of this specimen was $5.6 \times 10^5$ cycles.

At $N = 2.0 \times 10^5$ cycles, it was found from Fig. 10(a) that the leakage magnetic flux density, $B_z$, decreased around the specimen, although no apparent indication of the change in the distribution of $B_z$ was observed at the notch root.

At $N = 2.4 \times 10^5$ cycles, the magnetic flux densities showed the local decrease and take the minimum value at one of specimen edges where the notches were induced, as shown in Fig. 10(b). By an optical microscope, however, no crack was observed at both roots of the notches.

With the number of cycles increasing, this minimum value of magnetic flux density decreased. At $N=3.2 \times 10^5$ cycles, a crack was found by optical microscope. The location of crack initiation coincided with the location where the magnetic flux density took minimum value.

At $N = 4.2 \times 10^5$ cycles, it was found from Fig. 10(d) that the location of the minimum of the magnetic density moved to the center of the specimen, and it indicated the crack tip.

The changes in the leakage magnetic flux density, $B_z$, near the notch root, $(x, y)=(1.5, 1.5)$, are shown in Fig. 11. These fatigue tests were carried out at the nominal stress amplitude of 240MPa and 225MPa, respectively. It was found from Fig. 11 that the change in $B_z$ in the early stage of fatigue process was small. After a certain number of cycles just before crack initiation, the value of $B_z$ decreased. After crack initiation, the value of the magnetic flux density $B_z$ rapidly decreased with increasing the crack length.

The magnitudes of the change in the magnetic flux density for Type B specimen were smaller than those for Type A specimen. In Type B specimens, it was considered that the area for crack initiation site was small, and the martensitic transformation was also confined in small area around the notch root. Then the amount of the martensitic phase for Type B specimen was smaller than that for Type A specimen.

4. DISCUSSION

It was found that the behavior of the change in the magnetization of SUS304 specimen under cyclic loading depended on the stress ratio. For stress ratio, $R$, of $-1$, the change in magnetization was observed in the early stage of the fatigue process. On the other hand, for $R$ of 0.1, the change in the magnetization in the early stage of the fatigue process was small. This difference is considered to be related to the relationship between the martensitic transformation and stress-strain behavior. Martensitic transformations spontaneously occur at low temperature (martensitic transformation temperature: $M_s$). A mechanical driving force, such as stress, strain and deformation, causes martensitic transformation at room temperature. Additionally, the martensitic transformation causes strain hardening. Therefore, the magnitude of the maximum stress, which related to the hardening, is considered to affect on the behavior of the martensitic transformation.

Yakushiji et al. [5] reported that the martensitic transformation also depends on the temperature. The changes in the magnetization of SUS304 are affected by some kind of history, such as applied stress and temperature.

It is considered that the fatigue damage can be identified by the increasing rate of the magnetization independent of the stress ratio.

In the case of the stress rate of $-1$, the increasing rate of the magnetization for the stress amplitude above the fatigue limit was larger than that for stress amplitude below the fatigue limit. For stress ratio of 0.1, the
increasing rate of the magnetization during the crack propagation was larger than that before crack initiation. Therefore, when the increasing rate of the magnetization is large, the crack initiation is suspected.

5. CONCLUSIONS

For investigating possibility of the fatigue damage detection before crack initiation in austenitic stainless steel, SUS304, the change in magnetization in the fatigue process was examined. The leakage of magnetic flux density distribution was measured by the scanning system with MI sensor. The plain bending fatigue tests were carried out at several stress amplitudes and stress ratio of −1 and 0.1. It was found from the measurement results that the changes in the leakage magnetic flux density $B_z$ were observed before crack initiation and the location, where the maximum changes in $B_z$ observed, coincided with the location of the stress concentration, where a crack was detected.

The change in the leakage magnetic flux density distribution depended on the stress amplitude, the stress ratio and the number of cycles. The increasing rate of the magnetization was related to the fatigue damage independent of the stress ratio. The increasing rate of the magnetization was large just before crack initiation. When no crack was found, the increasing rate of the magnetization decreases with increasing the number of cycles, and the value of $B_z$ was saturated to a certain value. It was found that the detection and evaluation of fatigue damage before crack initiation can be conducted using the change in the magnetization in SUS304 steels.

REFERENCES