Investigation of Change Mechanism of Magnetic Flux Density Distribution around Fatigue Cracks

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Abstract
In order to clarify the changing mechanisms in the distribution of magnetic flux density around fatigue cracks during crack propagation, JIS SCM440 specimens were tested according to the following procedure: after fatigue testing to a crack length of 9 mm, the specimen was annealed. The fatigue test was then continued until the final crack length of 10 mm. The magnetic flux density was measured at 3 stages: once the crack reached 9 mm length, after the annealing process and once the crack reached 10 mm length. From the changes of the magnetic flux density distribution occurring at “the annealing” and “the fatigue testing after annealing” stages, it was concluded that these changes could be explained by the inverse magnetostrictive effect due to the residual stress caused by plastic deformation generated around the fatigue crack tip and accumulated along the crack path.

Keywords: NDT, Magnetic flux density, Fatigue Crack, Crack propagation, MI sensor

1. Introduction

In our previous studies[1][2], four-point bending fatigue tests under various conditions were carried out on JIS SCM440 steel specimens with artificial slits in order to develop a new non-destructive technique of fatigue evaluation based on magnetic information. In these studies the magnetic flux density distribution around the fatigue cracks was observed using a newly developed apparatus consisting of an MI (Magneto-Impedance) sensor and an x-y stage. Fig. 1 shows an example of the magnetic flux density distribution measurement results. It was found that the magnetic flux density distribution changed and moved along with crack propagation (as shown in Fig.1). A strong correlation between the movement of the magnetic flux density distribution and stress intensity factor was established, regardless of the loading conditions. Creating a non-destructive evaluation of the stress intensity factor for fatigue cracks by observing the relation between the two factors seems possible. However, the mechanism of the magnetic flux density distribution changes remains unclear.

When a magnetic material is subjected to mechanical load, the spontaneous magnetization of the material will change. This change is called “inverse magnetostrictive effect” [3] or “Villari effect”. This effect was closely studied in order to reveal the mechanism of the changes in the magnetic flux density distribution around fatigue cracks. Near the fatigue crack tip, plastic deformation occurs, and consequently the residual stress accumulates. This is known to influence the changes of the magnetic flux density distribution and in order to investigate this matter, specimens were annealed after the fatigue tests and then additional fatigue testing was performed on annealed material. The magnetic flux density distribution was observed at each step, and based on the observation results, the mechanism of the changes in the magnetic flux density distribution is discussed.
2. Experimental method

2.1 Experimental flow

In order to investigate the relationship between crack propagation, plastic deformation and magnetic flux density distribution, the following experiments were carried out:

Fig. 2 shows the flowchart of a series of conducted experiments. First, four-point bending fatigue test was carried out, and a fatigue crack was initiated. It then propagated to 9mm in length (Condition I). In this process, plastic deformation accumulated around the fatigue crack. Next, annealing of the specimen was carried out (Condition II) in order to reduce the plastic deformation around the fatigue crack. After annealing, an additional fatigue test was carried out till the crack length reached 10mm (Condition III).

The distribution of magnetic flux density and the FWHM of the X-ray diffraction profile of Condition I, II and III were measured and compared with each other, and the relationship between crack propagation, plastic deformation and magnetic flux density distribution were discussed. The details of the experiments are described in the following sections.

Fig.2 Flowchart of a series of experiments conducted in this study.
2.2 Specimen
The specimen material was chromium molybdenum steel, JIS SCM440. Fig. 3 shows the shape and dimensions of the specimen, which were 125mm (width) × 25mm (height) × 10mm (thickness). On one side and at the centre of the specimen, an artificial slit of 2.0mm length and tip radius $\rho = 100\mu m$ was made by wire electrical discharge machining. The surface was finished by polishing with abrasive paper #2000. The hardness of the specimen was about HV200.

![Fig.3 Specimen shape and dimensions.](image)

2.3 Crack growth tests
In this study, four-point bending fatigue tests were carried out using an electro-hydraulic servo fatigue testing machine (PSB-06, TAKES Group Ltd., Japan). Fig. 4 shows the four-point bending loading jigs. The support span was 100 mm and the load span was 50mm. Fatigue tests were carried out at a constant frequency of 20Hz, under maximum load $P_{max}$ of 15.8 and stress ratio $R$ of 0.1.
In order to control and measure the crack length, the fatigue tests were interrupted. A digital microscope (VH8000, KEYENCE, Japan) was used to measure the crack length.

![Fig. 4 Test jigs used for four-point bending fatigue test.](image)

2.4 Heat treatment
Annealing was carried out in nitrogen atmosphere under 873 K for 5 hours using an atmosphere furnace (TLG-40, Thermal Co. Ltd., Japan). In order to determine the heating conditions, preparatory experiments were carried out, and the effects of the annealing conditions on the microstructure of the specimen were investigated. Figs. 5(a) and 5(b) shows the microstructure before and after annealing at 873 K for 5 hours.
It was confirmed that the microstructure before and after the annealing was almost same, and composed of ferrite and pearlite.
2.5 Measurement of magnetic flux density distribution

Fig. 6 shows a photograph of the apparatus used for the magnetic flux density distribution measurements. The apparatus consists of a magnetic sensor, an x-y stage and a personal computer. Fig. 7 shows the MI sensor (AMI201, Aichi Micro Intelligent Corporation, Japan) used as the magnetic sensor in this apparatus. Fig. 8 shows a schematic illustration of the measurement area of the magnetic flux density. In this study, the xyz coordinate system illustrated in Fig. 8 was used.

By scanning the MI sensor on a 14 m × 7.6 m region at a height of 100 m from the specimen surface, as shown in Fig. 8, the magnetic flux density at each point in this area was measured. The scanning step was 0.2 m in both the x and y directions and the measuring time step was 1 sec/step. In this study, the x-component \( B_x \) of the magnetic flux density was measured at each point.
2.6 X-ray measurement
In order to understand the relation between crack growth, plastic deformation and magnetic flux density, the full width at half maximum (FWHM) of X-ray diffraction profiles were measured by using an X-ray diffractometer (M03XHF22, MAC Science, Japan).
The measurement conditions are shown in Table 1. FWHM measurement was carried out at every 1mm from $y = 3$mm to 11mm on the specimen surface.
In order to limit the diffraction area, the specimen surface was masked by a lead plate (thickness : 0.25mm) with a hole (diameter : 1mm).

<table>
<thead>
<tr>
<th>Characteristic X-ray</th>
<th>Cr-Kα</th>
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<tr>
<td>Diffraction plane</td>
<td>2 1 1</td>
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<tr>
<td>Diffraction angle $2\theta$, deg.</td>
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</tr>
<tr>
<td>Tube voltage, kV</td>
<td>30</td>
</tr>
<tr>
<td>Tube current, mA</td>
<td>30</td>
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</tbody>
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3. Experimental results and discussions
3.1 Effects of annealing after fatigue test
Figs. 9(a) and 9(b) show the distribution of FWHM of the X-ray diffraction profile of Condition I (before the annealing) and Condition II (after the annealing), respectively.
The dashed lines indicate the FWHM at the specimen’s end of the longitudinal direction. This represents the standard data without the influence of the crack.
In Fig. 9(a), with the increase in $y$, FWHM decreased towards the crack tip of $y= 9.0$mm, and then began to increase. It was considered that the dislocation density of the specimen before the fatigue testing was higher, and it decreased as the crack propagated due to plastic deformation generated around the crack tip and accumulated along the crack path.
The reason for the FWHM decrease towards the crack tip of $y= 9.0$mm would be explained by the increase of the stress intensity factor with the crack propagation.
On the other hand, in Fig. 9(b), the distribution of FWHM after the annealing was almost constant. The values were lower than before annealing and almost same as FWHM at the specimen end. The reason for this is thought to be the relaxation of the plastic deformation, generated in the crack propagation process, by the annealing.
Figs. 10(a) and 10(b) shows the distribution of the magnetic flux density around the fatigue crack of Condition I (before the annealing) and Condition II (after the annealing), respectively.
By comparing these figures, it was found that the value of the magnetic flux density decreased after annealing. This suggests a correlation between residual stress/plastic deformation, magnetic flux density and FWHM.
Fig. 9 Distribution of FWHM.

(a) Before annealing (After fatigue test)

(b) After annealing

(c) After additional fatigue test

Fig. 10 Distributions of magnetic flux density $B_x$.

(a) Before annealing (After fatigue test)

(b) After annealing

(c) After additional fatigue test
3.2 Effects of additional fatigue test after annealing

Fig. 9(c) shows the distribution of FWHM, Condition III (after the additional fatigue test). The shaded part, from $y = 9\text{mm}$ to $10\text{mm}$ in this figure, shows the range where the fatigue crack propagated in the additional fatigue test.

Comparing with Fig. 9(b) Condition II, the increase in FWHM was observed at the new crack tip (10 mm) and was almost constant elsewhere. It was considered that the dislocation density, once decreased by annealing, increased again around the crack tip. These results confirmed that the plastic deformation in Condition III occurred only in a localized area around the crack newly propagated.

Fig. 10(c) shows the distribution of the magnetic flux density, Condition III (after the additional fatigue test). In this figure, an increase of the magnetic flux density was also observed around the part where the crack propagated during the additional fatigue test.

A clear correlation was observed between the change of the magnetic flux density and FWHM by the additional fatigue test, as well as by annealing.

These changes of the magnetic flux density by annealing and additional fatigue test could be explained well by the inverse magnetostrictive effect.

From these results, it was concluded that the change of the magnetic flux density around the fatigue crack in its propagation process should be a result of the restraint of magnetic domains caused by the plastic deformation generated around the crack tip and accumulated along the crack path.

3. Conclusions

In order to reveal the mechanisms of the change in the magnetic flux density distribution around the fatigue crack in its propagation process, annealing after fatigue testing as well as additional fatigue testing after the annealing process were carried out. The changes in the magnetic flux density and FWHM around the fatigue crack occurring during these different measurement stages were observed. The following conclusions were obtained:

1. The magnetic flux density around the fatigue crack decreased through annealing, and a clear correlation between the change of the magnetic flux density and FWHM by the annealing was observed.
2. An obvious increase of the magnetic flux density was observed around the part where the crack propagated during the additional fatigue test after the annealing. In this region, FWHM also increased, and a good correlation was observed between the change of the magnetic flux density and FWHM by the additional fatigue test, as well as by annealing.
3. It was concluded that the change of the magnetic flux density around the fatigue crack in its propagation process was a result of the restraint of magnetic domains caused by the plastic deformation generated around the crack tip and accumulated along the crack path.

References