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General paper

Detection of Plastic Deformation and Fatigue Damage in Pressure Vessel Steel by Leakage Magnetic Flux Sensors

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Abstract: In order to detect material degradations in pressure vessel steel of A533B employed as a component material in light water reactors (LWRs), the leakage magnetic flux distribution on plate-type A533B specimens has been examined using a magnetic sensor of 120μm square GaAs Hall element. As reference data, the residual stress distribution has also been obtained by X-ray diffraction method where an irradiation spot was 1mm in diameter. The data of the leakage magnetic flux normal to the specimen surface (B_z) measured by the Hall sensor were converted into the form of the first derivative dB_z/dx by calculating the gradient of the B_z along the axial direction of the specimen (x-axis), and the data of the axial residual stress (σ_x) obtained by the X-ray diffraction method were also transformed into the differential form $d\sigma_x/dx$. It was found that there existed a correlation between the absolute value of the dB_z/dx and the $d\sigma_x/dx$ for the tensile specimens (correlation coefficient r =0.282). Full width at half maximum (FWHM) for the frequency distribution profile of the dB_z/dx was calculated. The FWHM of the tensile specimens increased remarkably at the beginning stage of the plastic deformation where the Lüder's band was generated; The FWHM of the fatigued specimens increased with stress cycling. It was suggested that the leakage magnetic flux measurement by the GaAs Hall sensor was a promising non-destructive evaluation (NDE) method to detect the amount of plastic deformation and fatigue damage.

Key words: *Pressure vessel steel, Leakage magnetic flux, Magnetic sensor, X-ray diffraction, Residual stress, Plastic deformation, Fatigue damage, Non-destructive evaluation, Statistical processing*

1. INTRODUCTION

In recent years, many efforts have been paid to the life extension activities for commercial light water reactors (LWRs) due to financial advantages and difficulties in locating a new nuclear power plant. In order to extend an operation period of existing plants, remaining life of the reactor components must be precisely estimated by detecting various material degradations such as plastic deformation and fatigue damage. A variety of techniques, such as destructive and non-destructive testing of actual components, and analytical estimation on the basis of material data and component operation history, have currently been adopted as the remaining life assessment. Among these techniques, the non-destructive assessment plays an important role during the pre-service and in-service inspections to evaluate the structural integrity of the LWR components.

Low cycle fatigue is one of the major problems for pressure vessels in LWR. Accordingly, adequate understanding of the change in residual stress states during operation period is required for maintaining the structural integrity. Although the X-ray diffraction method has already been well-established technique to estimate the residual stress by detecting microscopic deformation of crystal lattice nondestructively, it may be difficult to use X-ray apparatus in some cases because of its size. In terms of the size of the system, a leakage magnetic flux sensor appears to be a candidate for the residual stress measurement instead of the X-ray apparatus.

In the present study, the leakage magnetic flux distribution on plate-type tensile and fatigued specimens of pressure vessel steel A533B was investigated by using a semiconductor Hall element as a magnetic sensor. As reference data, the residual stress distribution was also obtained by the X-ray diffraction method, and a relationship between the leakage magnetic flux obtained by the magnetic sensor and the residual stress measured by the X-ray diffraction method was examined for the tensile specimens. The degree of the plastic deformation and fatigue damage accumulated in the specimens was estimated by statistical processing of the data of the leakage magnetic flux at each point obtained in the measurement.

2. EXPERIMENTAL

2.1. Material and Mechanical Testing

The material used was pressure vessel steel of A533B with chemical compositions as given in Table 1. This was annealed in N_2 gas at 600-650 °C for 2 hr, and then machined into plate-type specimens as shown in Fig. 1. The yield stress (0.2% proof stress) of the material was estimated to be about 520MPa. Tensile tests were carried out for the specimens to generate plastic strain in the range up to 8.0%. The strain was measured by a strain-gage attached on the center position of the specimen. Stress-controlled fatigue tests were also performed on the plate specimens under tension loading at stress ratio (R) of 0 (R: ratio of minimum stress to maximum stress).

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Table 1. Chemical compositions of a material used.

(mass %)

Material	C	Si	Mn	P	S	Cu	Ni	Mo	Al
A533B	0.18	0.14	1.53	0.004	0.002	0.03	0.66	0.56	0.010

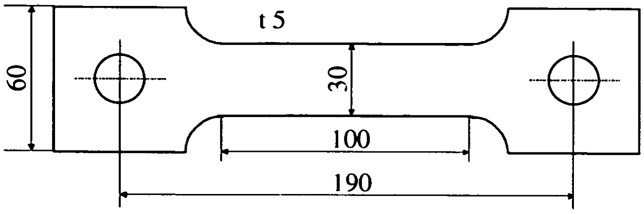

Fig. 1. Specimen configuration.

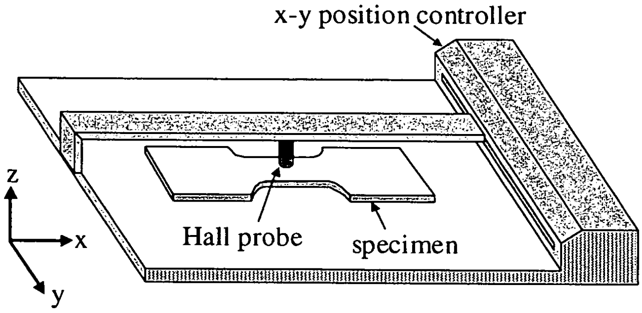

Fig. 2. Experimental setup for leakage magnetic flux measurement.

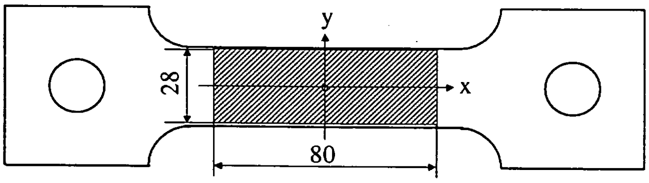

Fig. 3. Scanning area of leakage magnetic flux.

2.2. Measurement of Leakage Magnetic Flux Distribution

Figure 2 illustrates a schematic experimental apparatus for the magnetic flux measurement with an x-y position controller. The specimen was set on the apparatus with axial direction of the specimen parallel to the x-axis as shown in this figure. Ahead of the magnetic measurement, a polarization in a uniform field of 80kA/m dc field was performed along the axial direction of the specimen after demagnetization treatment [1-5]. Leakage magnetic flux normal to the specimen surface, B_z, was observed by using a Hall sensor. The physical origin to generate the leakage flux B_z is explained by the following mechanism [5-6]: Residual magnetization M of a sample is given by the vector sum of local magnetic moments $\rho(\mathbf{r})$ as follows:

$$M = \iiint \rho(\mathbf{r}) \cos[\theta(\mathbf{r})] dV, \tag{1}$$

which indicates that M is a function of locally different $\rho(\mathbf{r})$ and the angle $\theta(\mathbf{r})$ against the axial direction. $B(r)_z$ corresponds to z component (normal direction to specimen surface) of the magnetic flux density observed at a surface position r as

$$B(r)_z = \left[\mathrm{grad} \iiint \rho\ (\mathbf{r}) \cdot \frac{(\mathbf{r}-\mathbf{R})}{|r-R|^3} d^3R \right]_z . \tag{2}$$

In the present study, a 120μm square GaAs Hall element was employed as a Hall probe with a high sensitivity down to 10^{-8} T attained by the lock-in frequency of 10kHz. The Hall element was placed parallel to the sample surface with a lift-off of 200μm. The B_z distribution on the specimen was measured at intervals of 250μm within the area hatched in Fig. 3. The data of the B_z obtained in the measurement were converted into the differential form dB_z/dx by calculating the spatial gradient as a function of the axial position of the specimen: The dB_z/dx [unit: T/m] at $\mathbf{r}=(x,y)$ [mm, mm] position was obtained by dividing the difference between the B_z [mT] at $(x+0.5, y)$ [mm, mm] position and the B_z at $(x-0.5, y)$ position by 1 [mm]. The dB_z/dx is hereafter denoted as a magnetic parameter.

2.3. Measurement of Residual Stress Distribution

The X-ray diffraction method, which is employed as the residual stress measurement, examines lattice strain in the surface layers of a material. The strain is then converted into stress using various assumptions. The basic principle to derive the stress is very simple [6-9]. The interplanar spacing of a specific crystal plane is obtained from grains with different orientations by tilting and rotating the specimen with respect to the incident X-ray beam. The spacing d is estimated using the following Bragg's law:

$$2d \sin\theta = \lambda, \tag{3}$$

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where λ is the wavelength of the radiation and θ is the Bragg angle. The strain normal to a specific plane, $\varepsilon_{\phi\psi}$, is estimated using interplanar spacing as follows:

$$\varepsilon_{\phi\psi} = \frac{(d_{\phi\psi} - d_0)}{d_0} = \frac{\Delta d_{\phi\psi}}{d_0}, \tag{4}$$

where d_0 is the interplanar spacing for a stress free material, and $d_{\phi\psi}$ is the spacing in the direction $\phi\psi$, defined by the angles ϕ and ψ as shown in Fig. 4. Differentiating Eq. (3) and substituting into Eq. (4) gives

$$\varepsilon_{\phi\psi} = -\cot\theta_0 \cdot (\theta_{\phi\psi} - \theta_0) = -\cot\theta_0 \cdot \Delta\theta_{\phi\psi}, \tag{5}$$

where θ_0 is the Bragg angle for a stress free material, and $\theta_{\phi\psi}$ is the Bragg angle in the direction $\phi\psi$. The strain $\varepsilon_{\phi\psi}$ in the direction $\phi\psi$ can be related to the stress σ_x by

$$\varepsilon_{\phi\psi} = \frac{(1+\nu)}{E} \cdot \sigma_x \cdot \sin^2\psi - \frac{\nu}{E} \cdot (\sigma_1 + \sigma_2), \tag{6}$$

where E is the Young's modulus and ν is the Poisson's ratio of the material; σ_1 and σ_2 are the principal stresses. Differentiating Eqs. (5) and (6), and substituting results in

$$\sigma_x = K \cdot M, \tag{7}$$

$$K = -\frac{E}{2(1+\nu)} \cdot \cot\theta_0 \cdot \frac{\pi}{180}, \tag{8}$$

$$M = \frac{\partial(\Delta 2\theta_{\phi\psi})}{\partial(\sin^2\psi)}, \tag{9}$$

where K is the stress constant which depends on the material. For an isotropic material, a linear relationship is assumed between the $\Delta 2\theta_{\phi\psi}$ and the $\sin^2\psi$. Consequently the σ_x, axial residual stress, can be estimated by calculating the slope of Eq. (9).

In the present study, CrKα radiation (40kV, 30mA) and 211 diffraction plane were used. The stress constant employed was −318MPa per deg., and the irradiated spot on the specimen was 1mm in diameter. The σ_x distribution was measured only on the line of the y=0 (Fig. 3) at intervals of 2mm. The data of the σ_x was converted into the differential form $d\sigma_x/dx$ by calculating the ratio of the change in the σ_x to axial direction of the specimen: The $d\sigma_x/dx$ [unit: MPa/mm] at $\mathbf{r}=(x,y)$ [mm, mm] position was obtained by dividing the difference between the σ_x [MPa] at (x+2, y) [mm, mm] position and the σ_x at (x-2, y) position by 4 [mm]. The $d\sigma_x/dx$ is hereafter denoted as an X-ray parameter.

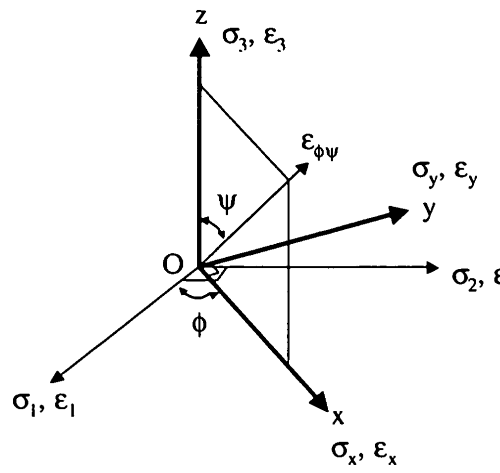

Fig. 4. Direction of the stress and strain.

3. THEORY

It has been reported that stress is a significant factor affecting the magnetization of the ferromagnetic materials [10-12]. In this section, the relationship between the magnetic parameter and the X-ray parameter has been derived theoretically. The residual stress is redistributed when plastic strain is applied in tensile test. The change in the residual stress affects both internal stress and microstructure in the specimen. The change in the internal stress influences the magnetic properties of the ferromagnetic material such as A533B because of an inverse magnetostrictive effect, resulting in a change in the magnetic permeability of the sample. The change in the microstructure is mainly observed in dislocation structure. The dislocation density D in a ferromagnetic single crystal is connected with initial magnetic susceptibility χ_0 as follows [13]:

$$\chi_0 \propto 1/\sqrt{D}. \tag{10}$$

Therefore, the change in the microstructure appears to influence the magnetic permeability of the A533B sample, although the sample is polycrystal. As a result of the polarization treatment after the demagnetization described in the Section 2.2, the redistributed residual stress is considered to give rise to the change in the residual magnetization of the sample for the contributions of the inverse magnetostictive effect and the change in dislocation density. Taking account of the derivation of the B_z from the residual magnetization as described in the Section 2.2, a correlation is assumed to be seen between the change in the axial residual stress σ_x and the change in the B_z: the absolute value of the X-ray parameter, $|d\sigma_x/dx|$, may correlate with the absolute value of the magnetic parameter, $|dB_z/dx|$. Next, the applicability of the correlation to the tensile sample of A533B will be discussed.

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4. RESULTS AND DISCUSSION

4.1. Relationship Between Observed Leakage Magnetic Flux and Residual Stress for Tensile Specimens

Figures 5 and 6 indicate the $|dB_z/dx|$ distribution on the y=0 line of the tensile specimen with plastic strain of 7.35% and 0.378%, respectively; Figs. 7 and 8 reveal the $|d\sigma_x/dx|$ distribution of the same samples. The specimen of the 0.378% plastic strain produced the Lüder's band, which corresponded to the area enclosed by gray color as shown in Figs. 6 and 8 where peaks and folds appeared remarkably. It appears from these diagrams that the $|dB_z/dx|$ distribution agrees with the $|d\sigma_x/dx|$ distribution. Correlation coefficient r between x and y can be calculated by the following formula:

$$r = \frac{\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\bar{x})^2 \cdot \sum_{i=1}^{N}(y_i-\bar{y})^2}}, \qquad (11)$$

where $\bar{x}$ and $\bar{y}$ are the mean values. The correlation coefficient between the $|dB_z/dx|$ and the $|d\sigma_x/dx|$ was calculated to be 0.282, which gives a weak correlation. Consequently, it was verified that the theory described in the former section was applicable to the tensile specimen of A533B.

4.2. Detection of Tensile and Fatigue Damage by Statistical Processing

In general, inhomogeneous deformation occurs during tensile and fatigue tests, and the distribution of the residual stress and the plastic strain is produced on the specimen. Therefore, it is supposed to be effective to estimate the degree of the plastic deformation and fatigue damage based on the distribution states of the B_z on the specimen. In the

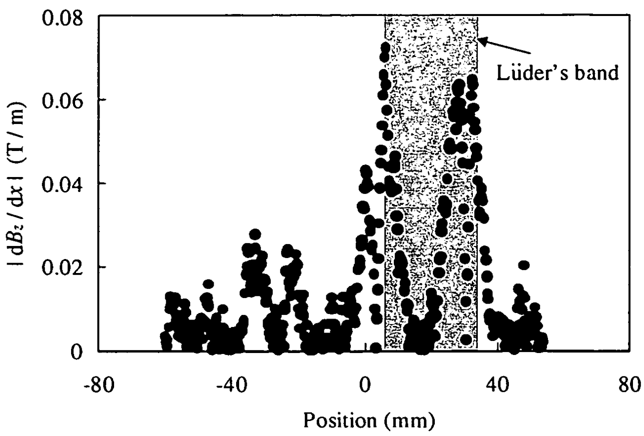

Fig. 6. $|dB_z/dx|$ distribution with 0.378% plastic strain on the line of y=0.

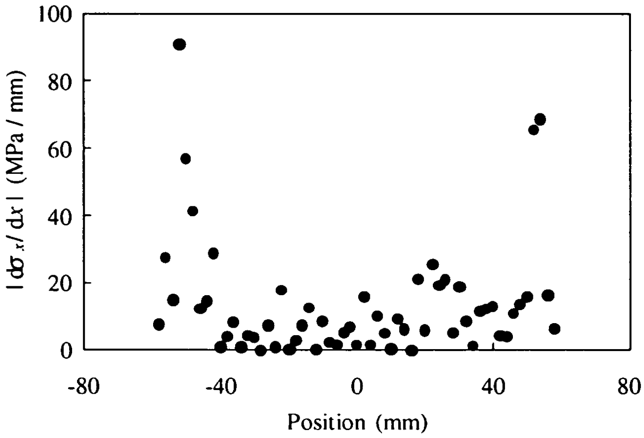

Fig. 7. $|d\sigma_x/dx|$ distribution with 7.35% plastic strain on the line of y=0.

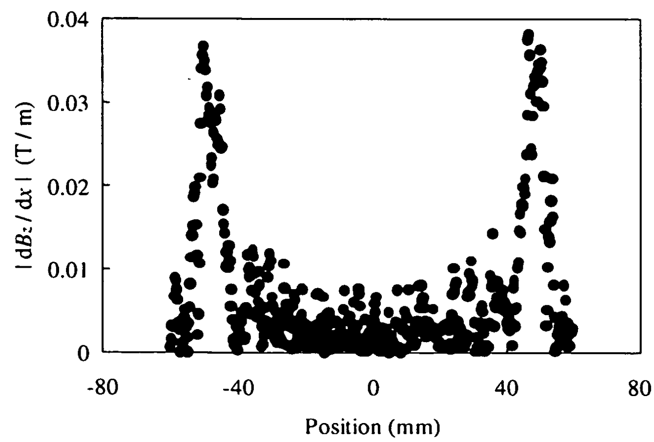

Fig. 5. $|dB_z/dx|$ distribution with 7.35% plastic strain on the line of y=0.

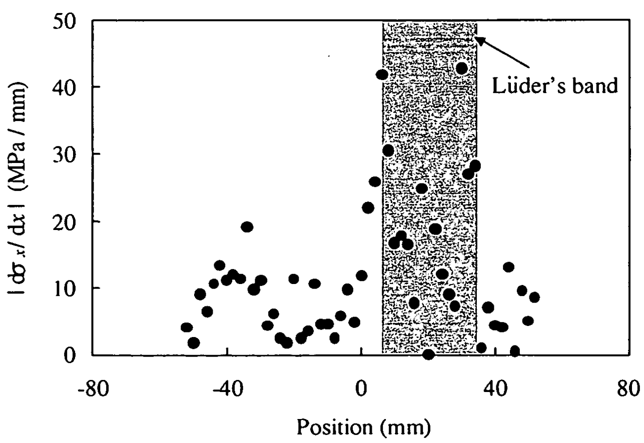

Fig. 8. $|d\sigma_x/dx|$ distribution with 0.378% plastic strain on the line of y=0.

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present study, the magnetic parameter dB_z/dx is employed to estimate them because the dB_z/dx appears to be more suitable parameter than B_z to detect local deformation. Figures 9 and 10 show the respective distribution states of the magnetic parameter dB_z/dx measured in the present study for the tensile and fatigued specimens where flux intensities are illustrated by gray scale. The frequency distribution of the dB_z/dx for the tensile and fatigued samples obtained by statistical processing is revealed in Figs. 11 and 12, respectively. It is found from Figs. 9 and 11 that the dB_z/dx distribution of the tensile specimen with 0.378% plastic strain, which generated the Lüder's band, is considerably more dispersive than those of the other specimens. Figures 10 and 12 signify that the dB_z/dx distribution for the fatigued specimen disperses with stress cycling. Accordingly, it appears that full width at half maximum (FWHM) for the profile of the dB_z/dx distribution is an appropriate parameter to describe the degree of the dispersion quantitatively. The FWHM of the tensile specimen as a function of the applied plastic strain is given in Fig. 13. This diagram indicates that the FWHM tends to increase remarkably at the beginning stage of the plastic deformation where the Lüder's bands are generated, suggesting that the early stage of the plastic strain could be detected during tensile test. Figure 14 re-

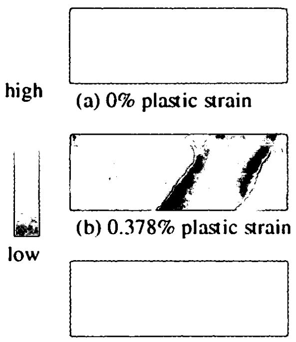

Fig. 9. Change in the pattern of the dB_z/dx distribution with plastic strain for the tensile specimens.

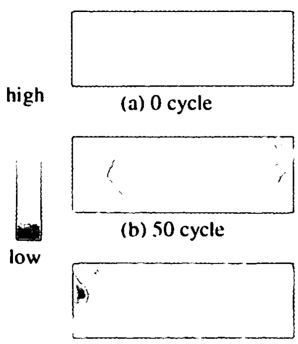

Fig. 10. Change in the pattern of the dB_z/dx distribution with stress cycling under stress amplitude of 500MPa for the fatigued specimens.

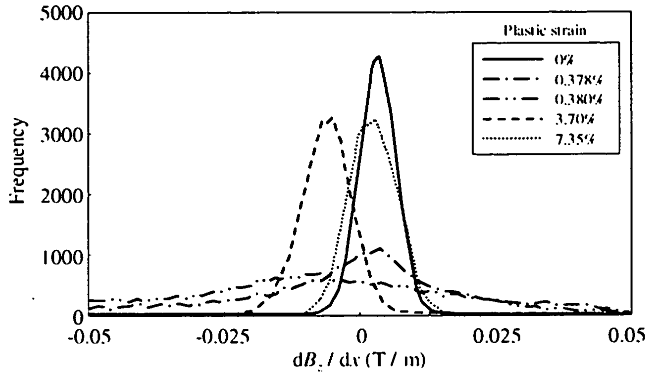

Fig. 11. Frequency distribution of the dB_z/dx for the tensile specimens.

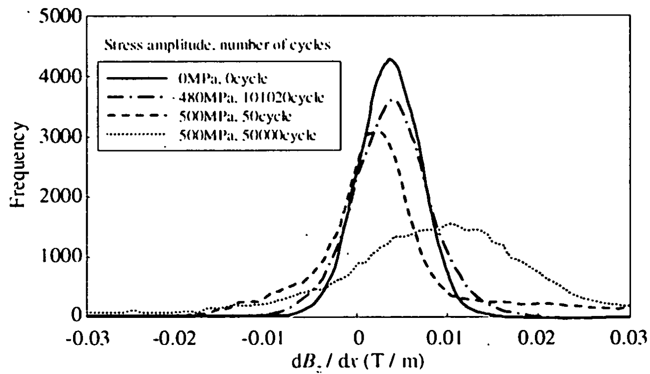

Fig. 12. Frequency distribution of the dB_z/dx for the fatigued specimens.

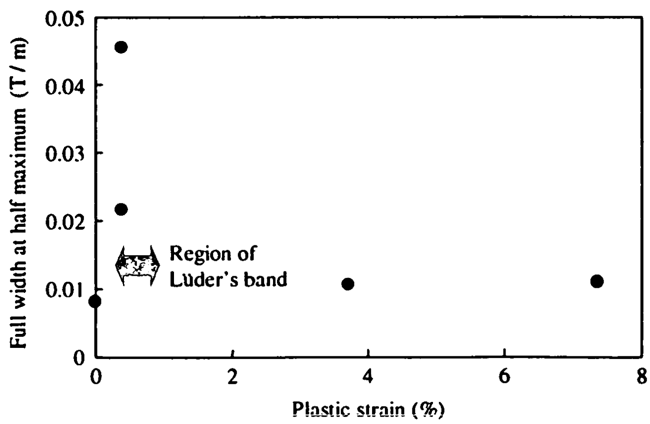

Fig. 13. Relationship between the full width at half maximum (FWHM) and applied plastic strain for the tensile specimens.

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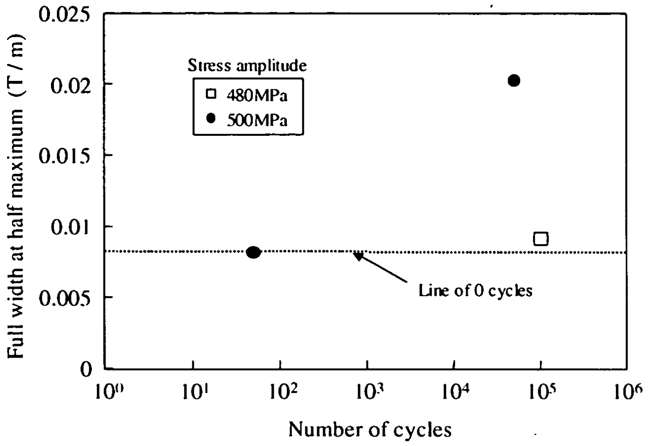

Fig. 14. Change in the full width at half maximum (FWHM) with stress cycling for the fatigued specimens.

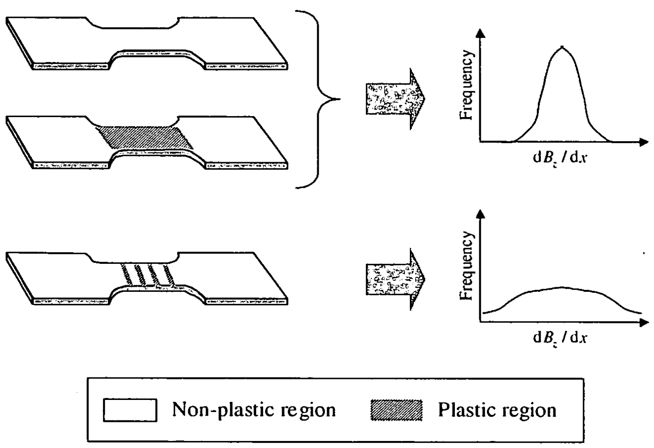

Fig. 15. Schematic illustration showing that the full width at half maximum (FWHM) for the frequency distribution profile of the dB_z/dx increases when both plastic and non-plastic region existed on the plate-type specimen.

veals the change in the FWHM with cycling for the fatigued specimens under stress amplitude of 480MPa and 500MPa, in which the value of the FWHM at 0 cycle is drawn by broken line. This figure represents that the FWHM tends to increase with increasing number of cycles, which implies the usefulness of the FWHM to detect the fatigue damage.

The mechanism of the increase in the FWHM can be explained as follows (see Fig. 15): It is assumed that magnetic properties are mutually different between plastic and non-plastic region. As a result, prominent peaks and folds occur in the dB_z/dx distribution on the border of their regions, which result in the increase in the FWHM when both the plastic and non-plastic regions exist on the specimen. It appears from the above results that the leakage magnetic flux measurement is a promising non-destructive evaluation (NDE) method to detect the beginnings of the plastic deformation and the fatigue damage in the pressure vessel steel.

5. CONCLUSION

In order to detect material degradations in pressure vessel steel of A533B employed in light water reactors (LWRs), the leakage magnetic flux distribution on plate-type specimens has been examined using a magnetic sensor of Hall element. As reference data, the residual stress distribution has also been obtained by X-ray diffraction method. The data of the leakage magnetic flux normal to specimen surface (B_z) measured by the Hall sensor were converted into the differential form dB_z/dx by calculating the gradient of the B_z along the axial direction of the specimen (x-axis), and the data of the axial residual stress (σ_x) obtained by the X-ray diffraction method were also transformed into the differential form $d\sigma_x/dx$. It was found that there existed a weak correlation between the $|dB_z/dx|$ and the $|d\sigma_x/dx|$ for the tensile specimens (correlation coefficient r=0.282). Full width at half maximum (FWHM) for the frequency distribution profile of the dB_z/dx was calculated through statistical processing. The FWHM of the tensile specimens increased remarkably at the beginning stage of the plastic deformation where the Lüder's band was generated, which suggested that an early stage of the plastic strain could be detected. The FWHM of the fatigued specimens increased with increasing the stress cycling, which implied that the fatigue damage could be detected. It was suggested that the leakage magnetic flux measurement by GaAs Hall sensor was a promising non-destructive evaluation (NDE) method to detect the amount of the plastic deformation and the fatigue damage in the pressure vessel steel.

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