

# MEASUREMENT OF THREE-DIMENSIONAL MAGNETOSTRICTION ON GRAIN-ORIENTED ELECTRICAL STEEL SHEET

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This paper deals with the magnetostriction of a grain-oriented electrical steel sheet measured by using the two-dimensional vector magnetic property measurement system and a three-axial strain gage. The magnetostrictions in arbitrary direction are calculated with the measured strain tensors. The magnetostriction characteristics were changed depending on the magnetization process according to the exciting magnetic flux density and the exciting direction. In this paper, we make clear the relationship among the two-dimensional magnetostriction, the magnetic flux density vector, and the magnetic field intensity vector in the grain-oriented electrical steel sheet.

**Keywords:** vector magnetic property, three-dimensional magnetostriction, grain-oriented electrical steel sheet, magnetization process

## 1 INTRODUCTION

In recent years, development of low acoustic noise and high efficiency transformers are a very important subject. It is therefore necessary to precisely evaluate magnetic property and magnetostriction of grain-oriented electrical steel sheets. In the conventional measurements, the magnetic property and the magnetostriction are usually measured in the exciting direction. However, the magnetic property is a vector quantity and the magnetostriction occurs not only in the exciting direction but also in any direction. We can consider that the magnetostriction also occurs in thickness direction as shown in Fig. 1. This figure shows schematic view of the general three-dimensional magnetostriction. The principal strain direction of the three-dimensional magnetostriction is not par-

allel to the magnetic flux density vector  $\mathbf{B}$  or the magnetic field intensity vector  $\mathbf{H}$  [1, 2].

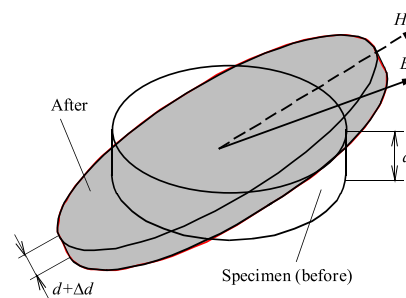


Fig. 1. Relationship among the three-dimensional magnetostriction and the vector  $\mathbf{B}$ , the vector  $\mathbf{H}$

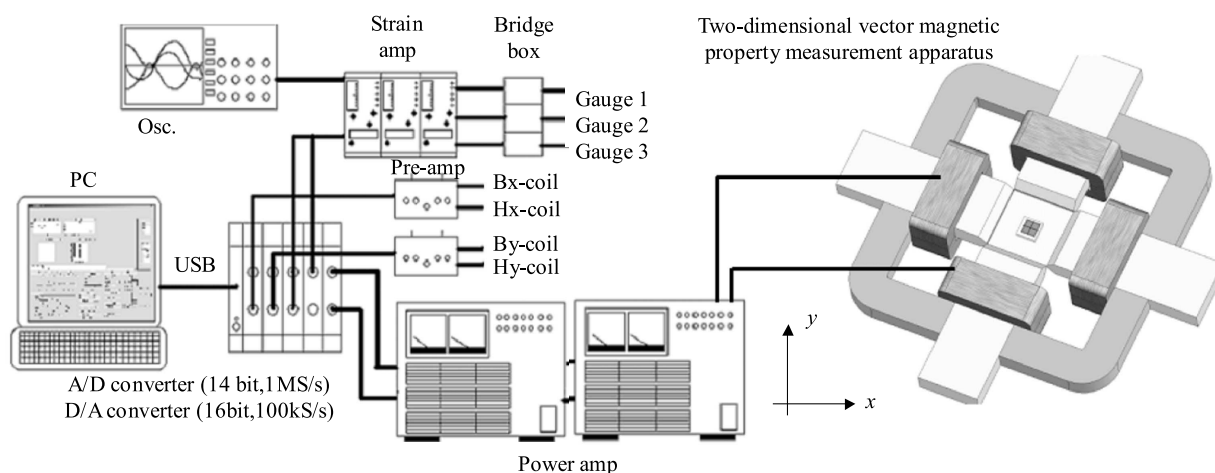


Fig. 2. Measurement system of the magnetostriction

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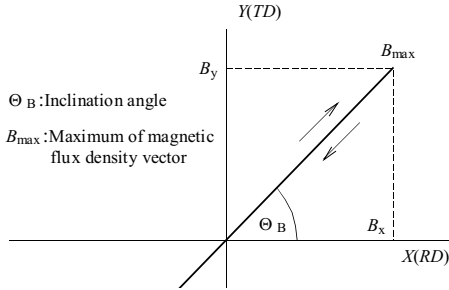


Fig. 3. Definition of the magnetic flux density condition

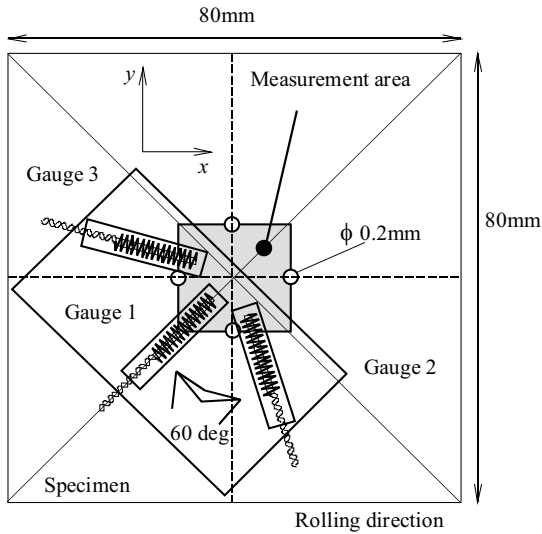


Fig. 4. Specimen and three-axial strain gauge

Table 1. The specification of the specimen

	Grain-oriented electrical steel sheet
Grade	35P135
Size	80 mm × 80 mm
Thickness	0.35 mm
Length of B-coil	20 mm
number of turns of B-coil	3 turn

Table 2. Measurement conditions

Specimen	$B_{\max}$ (T)	$\theta_B$ (degree)	$f$ (Hz)
35P135	0.1–1.1	0–90	50

We have measured the three-dimensional magnetostriction depending on the maximum magnetic flux density  $B_{\max}$  and its inclination angle from the rolling direction  $\theta_B$  by using the two-dimensional vector magnetic property measurement system and three-axial strain gauge. In this paper, we make clear the relationship among the magnetic flux density vector  $\mathbf{B}$  and the magnetic field

strength vector  $\mathbf{H}$  and the three-dimensional magnetostriction of a grain-oriented electrical steel sheet.

## 2 MEASUREMENT SYSTEM

### 2.1 Measurement system for magnetostriction

Figure 2 shows the measurement system of the magnetostriction based on the two-dimensional vector magnetic property measurement system [3, 4]. The components of the magnetic flux density,  $B_x$  and  $B_y$  were measured with cross-type search coils (B-coils) wound through holes. The hole's diameter was about 0.2 mm. The width of search coils was about 20 mm. The components of the magnetic field strength,  $H_x$  and  $H_y$  were measured with a double  $H$ -coil. The  $H_x$ -coil was wound over a 16 mm × 16 mm × 1 mm ceramic plate and the  $H_y$ -coil was wound over the  $H_x$ -coil. The double  $H$ -coil was placed under the specimen and pressed to touch the specimen.

The criterion of measurement was the magnetic flux density waveform in each direction. The each pickup voltage from the B-coils was freed-back controlled to be sinusoidal to generate arbitrary alternating magnetic flux in the measuring area, such as an alternating magnetic field inclined any direction. The convergence was judged with the amplitude, the phase, and the distortion factor of the pickup voltages. After the convergence, we adjusted the strain amplifier (KYOWA DPM-611) and measured the magnetostriction with a strain gage. Random noises were reduced by averaging the 32 cycles waveforms.

Figure 3 shows the alternating magnetic flux density condition. This condition is expressed with two parameters. They are the maximum magnetic flux density  $B_{\max}$  and the inclination angle  $\theta_B$ .  $\theta_B$  is an angle between the direction of  $B_{\max}$  and the rolling direction. The rolling direction was assumed to be 0 deg.

### 2.2 Specimen and three-axial strain gauge

Figure 4 shows the specimen and the three-axial strain gauge. Table 1 shows the specification of the specimen. The three-axial strain gauge (KYOWA SKF-5964) is a non-induction gauge. It is necessary to measure strains in three directions to derive the strain tensor and to estimate magnetostriction in arbitrary direction.

### 2.3 Two-dimensional magnetostriction

In order to obtain the magnetostriction in arbitrary direction, we used the following expression. Usually, the magnetostriction can be expressed as

$$\lambda = \frac{L}{\Delta L} = \sum_{i=1}^2 \sum_{j=1}^2 e_{ij} \beta_i \beta_j = e_{11} \beta_1 \beta_1 + 2e_{12} \beta_1 \beta_2 + e_{22} \beta_2 \beta_2 \quad (1)$$

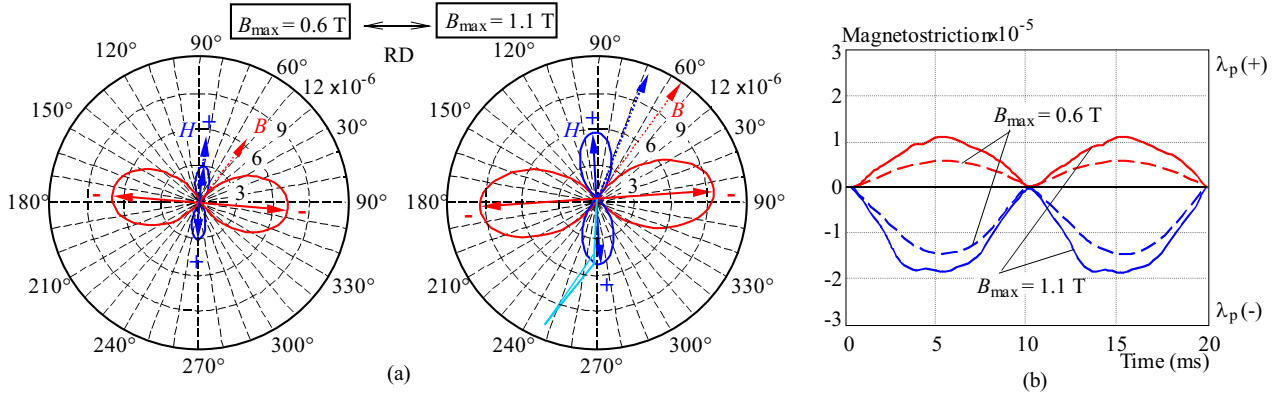


Fig. 5. Evaluation of the two-dimensional magnetostriction: (a) — two-dimensional magnetostriction, (b)— principal strain waveforms ( $\theta_B = 55$  deg)

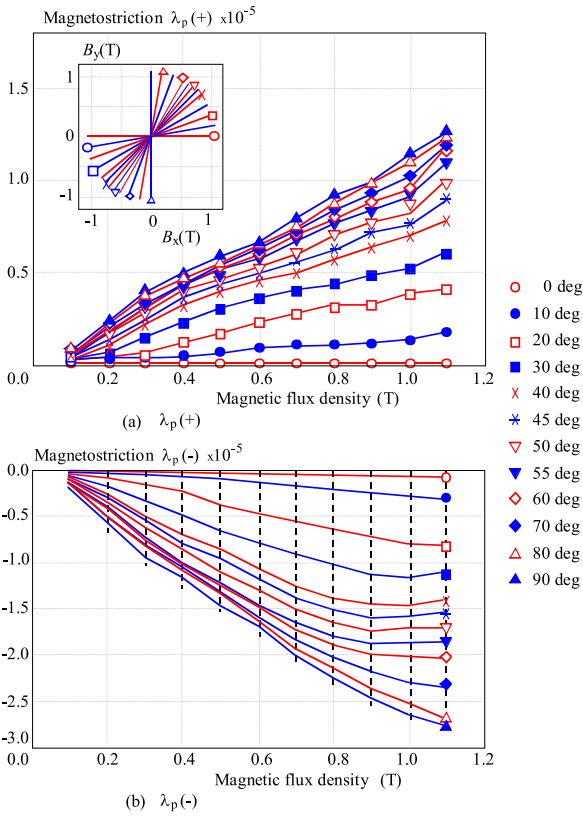


Fig. 6.  $\lambda_p(+)$  and  $\lambda_p(-)$  depending on  $B_{max}$  and  $\theta_B$

where,  $\lambda$  is the magnetostriction and  $e_{ij}$  is the strain tensor.  $\beta_i$  or  $\beta_j$  is the component of the unit vector. This equation can be rewritten as follows,

$$\begin{pmatrix} e_{11} \\ e_{12} \\ e_{22} \end{pmatrix} = \begin{bmatrix} (1 - \sqrt{3})/3 & 1/3 & (1 + \sqrt{3})/3 \\ 1/3 & -2/3 & 1/3 \\ (1 + \sqrt{3})/3 & 1/3 & (1 - \sqrt{3})/3 \end{bmatrix} \begin{pmatrix} \lambda_{gauge2} \\ \lambda_{gauge1} \\ \lambda_{gauge3} \end{pmatrix} \quad (2)$$

By substituting the strain tensor calculated with the equation (2) into the equation (1), we can obtain the magnetostrictions in arbitrary direction. We call this the two-dimensional magnetostriction.

### 3 EXPERIMENTAL RESULTS AND DISCUSSIONS

#### 3.1 Measurement conditions

Table 2 shows the measurement conditions.  $B_{max}$  was changed from 0.1 T to 1.1 T per 0.1 T step and  $\theta_B$  was changed from 0 deg to 90 deg. The excitation frequency was 50 Hz.

#### 3.2 Evaluation of two-dimensional magnetostriction

Figure 5 shows the measured results of the two-dimensional magnetostriction. The grey line shows the expansion and the grey arrow shows the principal strain of the expansion,  $\lambda_p(+)$ , which is the maximum magnetostriction. The black line shows the contraction and the black arrow shows the principal strain of the contraction,  $\lambda_p(-)$ .  $\lambda_p(+)$  occurred in 90 deg. and  $\lambda_p(-)$  occurred in 0 deg. The principal strains,  $B$ , and  $H$  were not parallel. We can point out that the conventional measurement is not enough. Figure 5(b) shows the  $\lambda_p(+)$  and  $\lambda_p(-)$  waveforms.

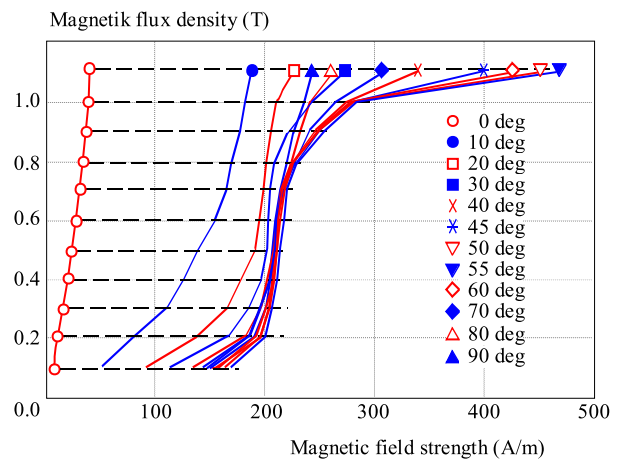


Fig. 7.  $\lambda_p(-)$  waveforms depending on  $B_{max}$  at  $\theta_B = 55$  deg

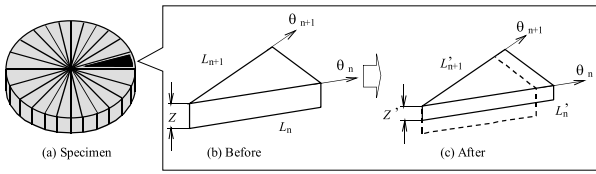


Fig. 8.  $\lambda_p(-)$  waveforms depending on  $\theta_B$  at  $B_{\max} = 1.1$  T

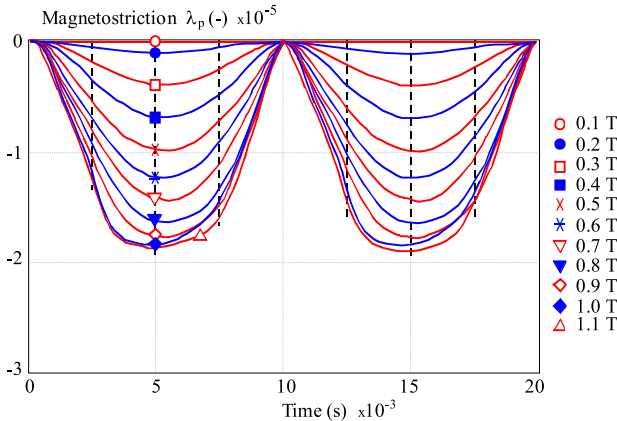


Fig. 9. B-H curves

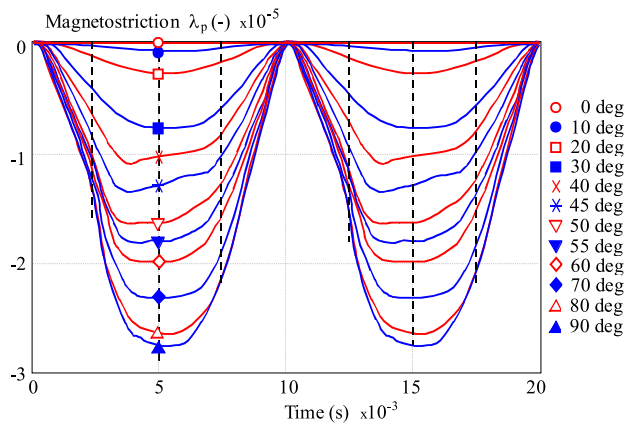


Fig. 10. Model for calculating  $\lambda_z$

### 3.3 Magnetostriction depending on $B_{\max}$ and $\theta_B$

Figure 6 shows  $\lambda_p(+)$  and  $\lambda_p(-)$  depending on  $B_{\max}$  and  $\theta_B$ .  $\lambda_p(+)$  and  $\lambda_p(-)$  increased with increasing  $B_{\max}$  and  $\theta_B$ . The magnetostriction became the minimum at  $\theta_B = 0$  deg. (the rolling direction) and the maximum at  $\theta_B = 90$  deg. (the transverse direction). This result is well known in the conventional measurement and called the magnetostriction anisotropy [5]. However, as shown in Fig. 6(b), the  $\lambda_p(-)$  decreased with increasing  $B_{\max}$  near  $\theta_B = 55$  deg. Figure 7 shows  $\lambda_p(-)$  waveforms depending on  $B_{\max}$  at  $\theta_B = 55$  deg, as an example. At the higher magnetic flux condition, the  $\lambda_p(-)$  waveforms

were distorted and peak-to-peak  $\lambda_p(-)$  did not increase due to the distortions.

Figure 8 shows  $\lambda_p(-)$  waveforms depending on  $\theta_B$  at  $B_{\max} = 1.1$  T. As shown in this figure, the distortions of  $\lambda_p(-)$  waveforms were changed depending on  $\theta_B$ . This phenomenon can be explained with the B-H curves as shown in Fig. 9. In this figure, the magnetic field strength corresponds to the maximum field strength  $H_{\max}$  and the magnetic flux density is the maximum flux density  $B_{\max}$ . At  $B_{\max}$  was 0.6 T,  $H_{\max}$  in  $\theta_B = 90$  deg was larger than one in  $\theta_B = 55$  deg. Inversely, at  $B_{\max}$  was 1.1 T,  $H_{\max}$  in  $\theta_B = 55$  deg was larger than one in  $\theta_B = 90$  deg. It is evident that the different magnetization processes depending on  $\theta_B$  influenced the magnetostriction.

The magnetostriction was larger in  $\theta_B = 90$  deg in comparison with that in  $\theta_B = 55$  deg, because a hard magnetizing direction around  $\theta_B = 55$  deg existed due to crystal anisotropy at the high magnetic field condition and in this state the rotational magnetization process should be main. As a result, it can be considered that the magnetostriction waveforms are distorted near  $\theta_B = 55$  deg. We can point out that it is important to measure the magnetic field strength with the magnetostriction to know the magnetization state.

### 3.4 Magnetostriction in thickness direction

The magnetostriction in thickness direction,  $\lambda_z$  is calculated with the measured data of the two-dimensional magnetostriction. Figure 10 shows the model for calculating  $\lambda_z$ . The specimen is divided into elements every direction. We can consider that the triangular pole element changes as shown in Figs. 10(b) and (c). Therefore, under assumption of constant volume,  $\lambda_z$  can be written as follows,

$$\lambda_z = \frac{1}{2} \frac{1}{(1 + \lambda_{\theta_n})(1 + \lambda_{\theta_{n+1}})} - 1 \quad (3)$$

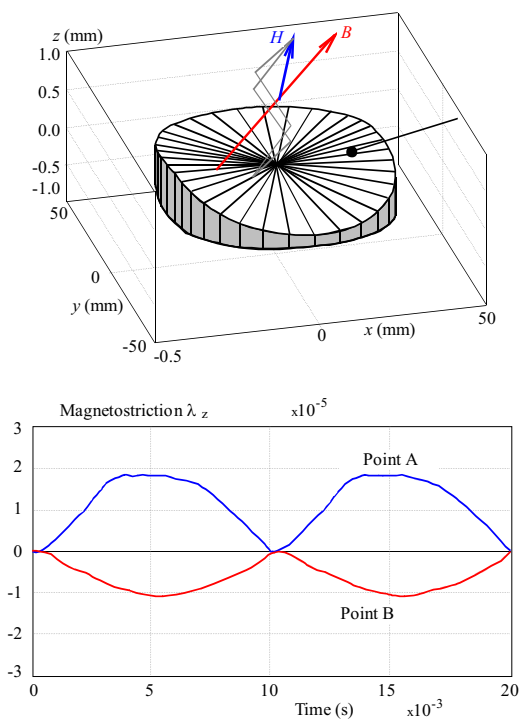
where,  $\lambda_{\theta_n}$  is the magnetostriction in  $\theta_n$  direction. We can estimate the three-dimensional magnetostriction including  $\lambda_z$ .

Figure 11 shows an example of the three-dimensional magnetostriction. Figure 11(a) shows the modified shape of the specimen due to three-dimensional magnetostriction. The thickness in the rolling direction increased and one in the transverse direction decreased. Figure 11(b) shows the magnetostriction waveforms in thickness direction at point A and B defined in Fig. 11(a).  $\lambda_z$  at the point A was larger than one at the point B. The magnetostriction in thickness direction also occurs similar to the magnetostriction in plane direction.

## 4 CONCLUSIONS

The three-dimensional magnetostriction property of the grain-oriented electrical steel sheet depending on the

maximum magnetic flux density  $B_{\max}$  and the inclination angle  $\theta_B$  are measured by using the two-dimensional vector magnetic property measurement system and three-axial strain gage. The principal strain of the expansion occurred in 90 deg and one of the contraction occurred in 0 deg. without depending on the inclination angle  $\theta_B$ . They were not parallel to the magnetic flux density vector,  $\mathbf{B}$  and the field strength vector,  $\mathbf{H}$ .  $\lambda_p(+)$  and  $\lambda_p(-)$  increased with increasing  $B_{\max}$  and  $\theta_B$ . However, the  $\lambda_p(-)$  decreased with increasing  $B_{\max}$  near  $\theta_B = 55$  deg. The hard magnetizing direction around  $\theta_B = 55$  deg existed due to crystal anisotropy at the high magnetic field condition and the rotational magnetization process is main in this state, therefore the magnetostriction was larger in  $\theta_B = 90$  deg in comparison with that in  $\theta_B = 55$  deg. From the above reason, the magnetostriction waveforms were distorted near  $\theta_B = 55$  deg.



**Fig. 11.** Three-dimensional magnetostriction at  $B_{\max} = 1.1$  T,  $\theta_B = 55$  deg

In this paper, we have pointed out that it is important to measure the magnetic field strength with the magnetostriction to know the magnetization state in the same

time and the magnetostriction in thickness direction to evaluate three-dimensional magnetostrictions in detail.

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