Magnetostriction and Domain Structure of Grain Oriented Silicon Steel Sheets

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The deformations by magnetostriction were measured on 3%Si-Fe (110) single crystal sheets with various deviation angles between the longitudinal direction and [001] axis. In the samples with small deviation angle contract in small field and expand in larger field. This result indicates 4th harmonic vibration will occur in the corner of transformer cores. The deformation is larger than that considering displacement of 180 degree wall followed by rotation magnetization. The deformation was explained by a domain structure composed by 90 degree domain walls.

Keywords: magnetostriction, domain wall, domain structure, silicon steel, rotation magnetization, single crystal, magnetization process, Kaya's law

I. Introduction

An acoustic noise of power transformers becomes a large problem. The main part of the noise is thought to be produced by magnetostriction of the cores of the transformers. If grain oriented silicon steel cores are used as the [001] axis parallel to the direction of flux, the deformations of the cores are very small because the movement of 180 degree domain walls never creates the deformation by the magnetostriction. However, at the corners of laminated core of transformers the [001] axis is not parallel to the direction of flux. Therefore a large deformation will be induced by the magnetostriction with the rotation of magnetization. Nevertheless the mechanism on the behavior of magnetostriction with the magnetization is not clarified by previous works⁽¹⁾⁻⁽⁵⁾.

In this paper, we report the experimental result about the deformation of 3%Si-Fe (110) single crystal sheets with applying the field deviated from [001]. In addition, the deformation is explained by magnetic domain structures.

II. Experimental Procedure

We used 3%Si-Fe single crystal sheets having (110) parallel to the surface by cut out from large grains of grain oriented silicon steel sheets. The sizes of the samples are 230

μm thickness, 60 mm length, and 5 mm width. The samples have various deviation angles between longitudinal direction and [001] direction as shown in Fig.1. The magnetostrictions are measured by 3-terminal capacitance method⁽⁶⁾. The measuring system is shown in Fig. 2. The deformation is measured as a change of the distance of fixed and movable electrodes. The system can measure the deformation and magnetization same time with applying the field because it has pickup coils for magnetization. In this study the directions of applying field and measuring the deformation and magnetization are the same as the longitudinal direction of the samples. The domain structure at different stage of the magnetization process was observed by using a scanning electron microscope⁽⁷⁾⁽⁸⁾ with acceleration voltage of 40 kV.

Fig. 1 (a) Sample preparation. (b) Measurement direction of deformation.

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Fig. 2 Schematic diagram of the measurement equipment.

III. Experimental Results

To clarify the magnetization process, we measure the magnetization curves of samples with various deviation angles. Fig. 3 shows the results. If the deviation angle is not zero, there are two points of changing the gradient of magnetization curve. We defined the point at smaller field as a primary crimp and the point at larger field as a secondary crimp. As shown in Fig. 3, magnetization greatly changed between the primary and the secondary crimp. As described below, the secondary crimp is very important point for the magnetization process of these samples. sized state to the secondary crimp and from the secondary

Fig. 3 Magnetization curves.

The deformation under the applying field was measured. Figures 4-8 show the results for samples with deviation angles of 10, 30, 45, 55, 90 degree. In each sample, there is a difference of the gradient in the deformation curve between smaller and larger field than the secondary crimp. In particular, as shown in Fig. 4, the sample with deviation angle of 10 degree contracts with applying small field and expands over the secondary crimp. These results mean there are two different mechanisms in the magnetization

processes of these samples.

In general, the deformation by the magnetostriction makes vibration of twice frequency of exiting frequency. The deformation curve measured above indicates a large 4th harmonic vibration at the corner of the transformer cores. To design the low-noise-transformers, it is important to take in the large 4th harmonic vibration at the corners of the core.

Fig. 4 Magnetization and deformation curve ($\alpha = 10^\circ$). Fig. 5 Magnetization and deformation curve ($\alpha = 30^\circ$). Fig. 6 Magnetization and deformation curve ($\alpha = 45^\circ$).

Fig. 7 Magnetization and deformation curve ($\alpha = 55^\circ$).

Fig. 8 Magnetization and deformation curve ($\alpha = 90^\circ$).

The magnetic domain pattern of the surface was observed with applying the field. At the demagnetized state, the domains were composed by 180 degree walls only. The 180 degree walls were parallel to the [001] axis. With applying the field larger than the primary crimp, diagonal walls appeared from the edge of the sample. At the secondary crimp, the diagonal walls occupied all the surface of the sample. Fig. 9 shows the domain structure of the 10 degree sample at near the secondary crimp. From the contrast of

Fig. 9 Magnetic domain structure of the 10° sample.

the domain pattern, we found the direction of the magnetization of each domain is parallel to the [001] axis and the diagonal walls are not parallel to the magnetization at the surface. It indicates a complex structure of the magnetic domains for minimizing the magnetostatic energy.

IV. Discussion

At the demagnetized state, the domains of the samples in this paper are composed by 180 degree walls. Therefore if the magnetization changed by the displacement of 180 degree domain walls followed by the rotation, the deformation between the demagnetization state to the saturated state of the samples in this paper can be calculated using the saturation magnetostriction constant⁽⁹⁾. However the calculated value of the deviation angle of 10 degree is as small as -1.3×10^{-6} . On the contrary, the observed deformation was -3.0×10^{-6} as shown in Fig. 4. In addition, if the magnetization changes by the displacement of 180 degree walls followed by the rotation, the deformation will not be observed during the displacement of 180 degree domain walls and the deformation by the rotation of magnetization will change monotonically. The observed deformation curves do not agree with these opinions.

To explain the results above, we proposed a formation of 90 degree domain walls between the primary and the secondary crimp. We made a model of the domain structure at the secondary crimp as shown in Fig. 10. This model satisfied the observed domain pattern on the surface. The volume ratio of [100], [010] and [001] domains are decided from the measured flux density at the secondary crimp. Furthermore there is no magnetic poles at every domain wall. In this model, each domain was divided by 90 degree walls.

Fig. 10 Proposed model of the domain structure with the state of the secondary crimp.

Using this model, the deformations from the demagnetization to the saturated state were calculated. Fig. 11. shows the calculated deformation on the deviation angles. Solid line shows the deformation from the demag-

netized state to the secondary crimp; broken line shows the deformation from the secondary crimp to the saturated state; and dotted line shows the deformation from the demagnetized state to the saturated state. From this figure it is recognized that when the deviation angle is less than 35 degree, the samples contract with applying the field less than the secondary crimp, and the samples expand with larger field. On the contrary, when the deviation angle is around 45 degree, the samples have the deformation of contraction only.

Fig. 11 Dependence of the calculated deformation on the deviation angle α .

The calculated value of the deformation was compared with the measured one. Fig. 12. shows the measured and the calculated deformation between the demagnetized state and the secondary crimp using the samples with various deviation angles. The calculated value agreed well with the measured one. This result means the model we proposed can explain the deformation of silicon steel sheets with deviation angles.

Fig. 12 Comparison of the calculated and measured deformation between the demagnetization state and secondary crimp.

V. Conclusion

We observed the deformation of 3%Si-Fe (110) single crystal sheets with various deviation angles between the longitudinal direction and [001] axis. The results are summarized as follows;

1. Large deformation was observed in samples than that considering the displacement of 180 degree walls followed by rotation magnetization.
2. The samples with the deviation angle less than 30 degree contract in small field and expand in larger field. This behavior makes large 4th harmonic vibration at the corners of transformer core.
3. The measured deformation was explained by magnetostriction under the creation of 90 degree walls during the magnetization process.

REFERENCES

- (1) Ya. S. Shur and V. R. Abel's: Phys. Met. Met., **63** (1958), 167
- (2) H. Hubert, W. Heinicke, and J. Kranz: Z. Angew. Phys., **19** (1965), 521.
- (3) K. Narita and T. Yamaguchi, IEEE Trans. Magn., **MAG-11** (1975), 1661.
- (4) M. Enokizono, G. Shirakawa, T. Suzuki, and J. D. Sievert: J. Magn. Soc. Jpn., **15** (1991), 265.
- (5) A. Saito, S. Ueda, K. Yamamoto, S. Murashige, and J. N. Nderu: J. Magn. Soc. Jpn., **17** (1993), 241.
- (6) A. M. Thompson: IRE Trans. Instr., **I-7** (1958), 245.
- (7) D. J. Fathers, J. P. Jakubovics, D. C. Joy, D. E. Newbury, and H. Yakowitz: Phys. Stat. Sol., (a) **20** (1973), 535.
- (8) T. Yamamoto and K. Tsuno: AIP Conf. Proc., Magn. Mag. Mater., **29** (1975), 572.
- (9) S. Chikazumi: Physics of Ferromagnetism vol. 2, Syokabo, Tokyo, (1984), p.116.