Effects of magnetic field applied during heat treatment on magnetic properties of non-oriented electrical steel sheets

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To improve the magnetic properties of non-oriented electrical steel sheets, the effects of applying heat treatment in a magnetic field on controlling the crystallographic orientation were studied. The heat treatment temperature was controlled to be 1023, 1123, and 1273 K. The magnetic field applied during the treatment was parallel to the rolling direction of sheet samples, and the magnetic field strength was 10 T at maximum. The samples heat treated in a magnetic field under the temperature condition of 1123 K or higher showed a remarkable change in magnetic direction of sheet samples, and the magnetic field strength was 10 T at maximum. The samples heat treated in a magnetic field throughout the heat treatment, i.e. heating and cooling, inhibited grain growth, increased iron loss, and decreased magnetic permeability.

Key words: magnetic heat treatment, crystallographic orientation, iron loss

1. Introduction

There is an international demand for effective utilization of energy, especially for downsizing and improving efficiency of rotating electric motors (hereinafter referred to as electric motors), which account for a large proportion of total electric power consumption. The efficiency of electric motors is specified by the IEC standards, and the efficiency class is defined from the IE1 (standard efficiency) to the IE3 (premium efficiency). It is expected that demand for higher efficiency of electric motors will further increase in future.

Responding to the needs, effort to improve efficiency of electric motors and decrease energy losses, e.g. core losses, should be considered. Iron loss is known to increase due to the influence of residual stress during iron core processing, thereby deteriorating the magnetic properties. In order to reduce iron loss without changing the iron core material, it is expected that reduction or utilization of residual stress is necessary.

Strain relief annealing is an effective method to reduce residual stresses. In non-oriented electrical steel sheets, deterioration of magnetic properties due to processing strain is known to be improved by heat treating at about 1020 K\(^1\). However, strain relief annealing leads to texture changes within the material. A structure including hard axis of magnetization based on magneto-crystalline anisotropy appears in the plane of the electrical steel sheet, resulting in the deterioration of magnetic properties at 1.5 T or higher. Thus, it may not be possible to take full advantage of material properties with simple heat treatment\(^2,3\). Therefore, the authors’ group has studied heat treatment in a magnetic field which offers the possibility of controlling the texture of the magnetic material during heat treatment.

It is well known that magnetic properties of magnetic materials are improved by heat treatment in a magnetic field\(^4\). In addition, some literatures reported that the material’s texture could be controlled with such heat treatment processes\(^5,6\). However, there are few detailed reports on the magnetic properties under alternating excitation of non-oriented electrical steel sheets heat-treated in a magnetic field. Moreover, detailed mechanism of the phenomenon is not well understood and there are only a few reports on their industrial application. The authors in present study investigated the effects on the magnetic properties under alternating excitation of samples heat-treated in a magnetic field by using commercially available electromagnetic steel plates. In our previous reports, samples of sufficient size could not be produced due to the structural
constraints of heat treatment equipment, and there was only qualitative discussion[7]. Subsequently, quantitative evaluation methods of samples with shape constraints were studied, and the magnetic properties in the direction of the magnetic field applied during heat treatment were measured with a small-sized single sheet tester (SST) [8]. In this paper, by comparing magnetic properties with and without a magnetic field during heat treatment, we make clear quantitatively magnetic properties depending on heat treatment conditions, i.e. temperature and magnetic field.

2. Experimental method and apparatus

2.1 Heat treatment apparatus in a magnetic field

Fig. 1 shows a schematic view of the heat treatment apparatus. The heat treatment apparatus in a magnetic field consisted of a superconducting magnet (10 T-CSM) with an inner diameter of 100 mm, and a quartz glass tube with outer diameter of 14 mm and inner diameter of 12 mm of which one end was closed. The quartz glass tube was inserted into an electric furnace with an outer diameter of 50 mm and an inner diameter of 22 mm. The structure could be depressurized to less than 10⁻³ Pa with a turbo molecular pump. Samples were prepared by cutting a non-oriented electrical steel sheet 50A470 (JIS C 2552) to 10 mm × 50 mm by electrical discharge machining, and set at the center of the magnetic field in the quartz tube using a holding jig made of quartz so that the field direction of the magnetic field was parallel to the longitudinal direction of the sample. Thus, the uniformity of the magnetic field during the heat treatment at the sample position was sufficiently maintained. The temperature around the sample was measured using a Pt-Rh thermocouple.

Fig. 2 shows the temperature profile and applied magnetic field pattern. In this test, the temperature was raised to the set temperature at a rate of \( T/t_1 \) = 500 K/hr, and after reaching the set temperature, the sample was held for \((t_2 - t_1) = 1 \text{ hr}\), and then cooled to room temperature at a rate of \( T/(t_3 - t_2) \) = 100 K/hr. A constant magnitude of magnetic field was kept throughout the heating and cooling cycle until the sample was cooled to room temperature.

2.2 Small-sized Single Sheet Tester (SST) [8]

Fig. 3 shows the measurement system of SST, and Fig. 4 shows the schematic diagram of the apparatus configuration. As an excitation coil, polyester copper wire (PEW), φ1.0 mm, was wound for 380 turns on the epoxy resin frame. As a yoke, 20 electrical steel sheets (50A470) cut out by electrical discharge machining were used, and laminated and adhered in the direction of the paper surface of Fig. 3 to a thickness of 10 mm or more. By using the stacked yokes, leakage of magnetic flux is prevented and generation of eddy currents is reduced. Samples were formed by electrical discharge machining of electrical steel sheets (50A470) to be 10 mm × 50 mm, with the rolling direction being the longitudinal direction of the sample. A measurement sample placed in the central part of the excitation coil is excited by alternating magnetic flux in the longitudinal direction to measure the alternating magnetic properties of 50 Hz. As shown in Fig. 3, feedback control can be performed in this system, and a sinusoidal magnetic flux density waveform in the sample is maintained. The magnetic flux search coil (B-coil), of 3 turns is wound at the central portion of the sample, and the magnetic flux

![Fig. 2 Schematic diagram of magnetic field during heat treatment.](image)

![Fig. 3 System for measuring magnetic properties of SST.](image)

![Fig. 4 Schematic diagram of SST configuration.](image)
density $B$ is thereby detected. The magnetic field strength $H$ is calculated from the excitation current detected by the shunt resistance. The effective magnetic path length $l$ is determined as the yoke inner dimension (40 mm). Based on the above conditions, multiple samples were measured a number of times, and the average value was taken as the measurement result.

3. Experimental results and discussion

3.1 Effect of heat treatment temperature

To understand the effects of heat treatment in a magnetic field on the magnetic properties of the electrical steel sheets, heat treatment in the absence of a magnetic field was firstly carried out. The heat treatment temperatures for comparison were 1023, 1123, and 1273 K. Samples were heated at 330 K/hr, held for 1 hr, and then cooled to room temperature at 100 K/hr. Same cooling and heating rate was used regardless of the heat treatment temperature. Fig. 5 shows the iron loss measurement results of the samples fabricated at each heat treatment temperature. It was found that the iron loss decreased under all conditions as compared with ones before heat treatment. In addition, the iron loss also decreased as the heat treatment temperature increased.

Next, magnetic permeability characteristics depending on the heat treatment temperature were investigated. Fig. 6 shows the measurement results of the magnetic permeability. Compared with the relative permeability of the electrical steel sheets before heat treatment, the relative permeability increased with the excitation magnetic flux density of 1.5 T or less under all the temperature conditions. In addition, the magnetic permeability increased as the heat treatment temperature increased. Reduction of the iron loss and increase of the relative permeability may be attributed to grain growth.

Fig. 7 shows an image of crystal grains observed with an optical microscope. As expected, the crystal grains became coarser compared with those before heat treatment. The grain size of the sample heat-treated at 1273 K increased to nearly 1 mm. Thus, the increase of the magnetic permeability can be explained by the relative reduction of crystal grain boundary areas, which constitute an energy barrier, resulting in the reduction of iron loss due to facilitated magnetic domain wall movement. As for the excitation magnetic flux density of 1.6 T or higher, the iron loss was reduced, but the magnetic permeability decreased as compared with that before heat treatment. The reason that the permeability decreases in the high magnetic field of ≥1.6 T is due to the fact that the 90° magnetic domains with respect to the excitation direction are increased by the heat treatment. Normally the <100> direction, i.e. the easy direction of crystal magnetization, is largely distributed within the plane in order to reduce spontaneous magnetization in thickness direction. However the heat treatment promoted isotropic grain growth resulting in increased <100> crystals in the...
It was found that the magnetic properties of electrical steel sheets subjected to simple heat treatment deteriorated at the exciting magnetic flux density of ≥1.6 T. The reason for poor properties is the spontaneous magnetization in the thickness direction of the steel sheet due to isotropic grain growth. Therefore, by applying a magnetic field during heat treatment, spontaneous magnetization in the thickness direction of the steel sheet is expected to be suppressed, resulting in good magnetic properties even in a high excitation field.

The anisotropy induced by heat treatment of soft magnetic materials in a magnetic field is often explained in terms of magnetic atom pair ordering mechanism. According to the model for binary alloys proposed independently by Néel and Taniguchi, the directional diffusion takes place with a preferred direction of magnetic atom pairs imposed by the direction of magnetization during the heat treatment and/or subsequent cooling. This explanation should be applied to materials with directional-ordered crystallographic microstructure. Since the material used in this study has a few percent of silicon and it is seldom the ordered lattice structure, the above model is not considered to be dominant. A previous study reported that texture could be controlled by applying a magnetic field to electrical steel sheets during the cooling step of the heat treatment. Hence, the application of magnetic field during cooling step improves the magnetic properties of electrical steel sheets. In the present study, the heat treatment temperature of the sample was set to 1123 K and 1273 K at which the iron loss reduction effect was particularly marked, and a magnetic field was applied during cooling. The applied magnetic field strength was set to 1 T, 5 T, 10 T, and the effects of the heat treatment temperature and the magnetic field strength applied during cooling on magnetic properties were investigated. Fig. 8(a) shows the changing rate of iron loss characteristics of the samples heat-treated at 1123 K in a magnetic field relative to one of the sample heat-treated in the absence of a magnetic field. At 1 T and 5 T, the iron loss increased with its ratio greater than 1, but at 10 T, the iron loss was reduced in all regions. Although the detailed mechanism is not completely understood, the application of a magnetic field during cooling clearly affected the magnetic properties. In the sample subjected to heat treatment in a magnetic field at 1273 K, as shown in Fig. 8(b), the iron loss is reduced in almost all regions by applying the magnetic field. Although at 1123 K, a correlation with the magnetic field strength was not confirmed, at 1273 K it was found that iron loss could be further reduced by increasing the magnetic field strength. This experimental result suggests that raising the heat treatment temperature increases the sensitivity of the sample to the magnetic field.
Next, the change in the relative permeability due to heat treatment in the magnetic field was examined. Fig. 9(a) shows the measurement result of the changing rate of the relative magnetic permeability of the sample heat-treated in the magnetic field at 1123 K, and Fig. 9(b) shows the result at 1273 K. As seen from Fig. 9(a), at ≤1.3T, the relative permeability of the samples heat-treated in the magnetic field decreased, and the decrease rate of the sample heat-treated at 1 T is the largest. Although a slight increase in magnetic permeability was observed between 1.4 T and 1.6 T, the relative permeability ratio at ≥1.8 T decreased to less than 1. In Fig. 9(b), by applying a magnetic field (neglecting 1 T), the magnetic permeability decreased in the sample heat-treated at 1273 K under relatively low excitation conditions and increased under high excitation conditions. The behavior of this relative permeability was observed independently at different temperature in heat treatment. However, the changing rate of the relative permeability with respect to the magnetic field was larger at higher temperature i.e. 1273 K. Similar to iron loss, the sensitivity of magnetic properties to the magnetic field during heat treatment is higher for samples heat treated at high temperature.

The change in magnetic properties could be possible due to change in texture of the sample caused by the application of the magnetic field during heat treatment. In order to evaluate the texture of a sample heat-treated in the magnetic field, X-ray pole figure measurement was performed. Fig. 10 shows the (110) X-ray pole figure measurement results for the samples (a) before heat treatment, and (b), (c), after heat-treated at 1123 K and 1273 K, respectively. In Fig. 10, the region enclosed by the red line is a strong intensity position, indicating the presence of a texture. At 1123 K, only minor changes were found compared with before heat treatment. At 1273 K, the texture was greatly changed and high intensity diffraction lines could be seen at the center of the (110) pole figure, indicating that (110) increased in the plane parallel to the surface of the steel sheet. Since (110) is the plane orientation including both the <100> direction which is the easy magnetization direction and the <111> direction which is the hard magnetization direction, it is expected that magnetization properties improved in the <100> direction. However, in the longitudinal direction of the sample which is the measurement direction, i.e. in the direction of the magnetic field during heat treatment, improvement of magnetization properties could not be confirmed. The induced magnetic anisotropy in the non-oriented electrical steel sheets is considered to be a large influence of crystal orientation. The sample subjected to heat treatment in the magnetic field undergoes a recrystallization process accompanied with preferred orientation, whereby the crystal orientation distribution changes and anisotropy appears. As the conditions under which the anisotropy was induced, in the present experiments, both of a sufficient temperature condition for causing recrystallization and a strong magnetic field capable to give non-negligible influence on the scattering by the temperature are necessary. We believe, by clarifying the relationship between magnetic field applied during heat treatment and the resulting crystal orientations, crystal directions that improve magnetic properties of steels could be determined and preferentially textured within the material.

3.3 Effect of magnetic field applied during heating

An electrical steel sheet made of iron to which a few percent of silicon is added becomes a paramagnetic substance at and above the Curie temperature. The sheet does not exhibit spontaneous magnetization, suggesting that it is not likely to easily get affected by a magnetic field above the Curie temperature. However, Bacalchuk et al. reported that application of a magnetic field in the temperature range showing paramagnetism was effective to control texture\(^{13}\). In addition, by applying a magnetic field in the ferromagnetic state, individual crystal grains may generate magnetostriction and expand or contract according to the crystal orientation. An energy barrier is then formed at the crystal grain boundaries which interferes with grain growth\(^{14,15}\), resulting in deterioration of magnetic properties. Hence, the effects of the magnetic field may not necessarily be obtained under ferromagnetic conditions in soft magnetic materials against that magnetic properties are expected to improve by heat treatment in a magnetic field. As described in the previous section, the effects of the magnetic field are more pronounced when applied during heat treatment at ≥1123 K, which is believed to exceed the Curie temperature. Therefore, by comparing the magnetic properties of a sample to which a magnetic field was applied only during the cooling to a sample produced by continuous application of a magnetic field throughout heating and cooling, we examined the heat treatment condition under which the magnetic field was more effective with respect to material’s magnetic properties. The measurement condition are selected to be 1 T and 10 T at 1273 K of which the effects of the magnetic field
The magnetic flux density, magnetic permeability ratio decreased in the range of 0 to 1.5 T. This is believed to be the result of crystal growth during heat treatment under the magnetic field, as seen in Fig. 12. The second reason may be an increase in the 90° magnetic domain structure changes remarkably.

Since $\lambda_{113}$ which is a typical magnetostriction constant of iron is a negative value, the sample may contract in the magnetic field direction if a strong magnetic field is applied at a temperature below the Curie temperature.

By maintaining the contracted state while being exposed to a high temperature, crystal grains grow with a relatively large number of 90° magnetic domains, resulting in microstructural texturing. We believe that this phenomenon would be better understood and explained in future works by detailed observation of crystal growth and boundaries inside the sample and observing the changes in magnetic domains. Furthermore, in addition to the magnetic field application conditions verified in this paper, experiments will be carried out the application of a magnetic field only during heating up to certain temperature and only during keeping, we make clear a suitable heat treatment condition, which is most effective to material's magnetic properties.

4. Conclusion

In this paper, the effects of heat treatment in an applied magnetic field on the magnetic properties of the commercial electrical steel sheet (50A470) were reported. Upon heat treating in the absence of magnetic field, grain growth was promoted and iron loss was reduced with increasing heat treatment temperature. The relative permeability, however, decreased at the alternating excitation condition of $\geq$1.6 T. The magnitude of the influence of the magnetic field varied with heat treatment temperature, and greater effects were seen at higher temperature. These effects also varied depending on whether the magnetic field was applied throughout the heat-treatment or during cooling alone. Iron loss was seen to increase and magnetic permeability decrease with 10 T magnetic field applied throughout heating and cooling, as compared with 10 T applied during cooling only. The results demonstrate that the strength of magnetic field and whether the magnetic field is applied during cooling or throughout the heat treatment process are both important parameters.
Results confirmed the change in texture of non-oriented electrical steel sheet due to heat treatment in magnetic field, ultimately affecting the magnetic properties under alternating excitation. In future works, we will clarify the phenomenon whereby the magnetic properties change due to heat treatment in a magnetic field by analyzing detailed observation of crystal orientation distribution and crystal grain boundaries using EBSD or XRD, by observing the change of magnetic domain structures using Kerr effect, and by measuring the two-dimensional magnetic properties.

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