Iron Loss Deterioration by Shearing Process in Non-Oriented Electrical Steel with Different Thicknesses and Its Influence on Estimation of Motor Iron Loss

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The influence of the shearing process on the iron loss of non-oriented electrical steels with thicknesses of 0.20–0.50 mm was investigated. The deterioration of material iron loss was lesser in thinner steel sheets. The distribution of the increase in hardness near the sheared edge was almost half of the sheet thickness for all tested steels. Therefore, applying thinner steel sheets for the motor core may decrease the iron loss deterioration from the punching process. This argument was supported by measuring the iron loss of a model IPMSM using steels with different thicknesses and calculating the motor iron loss through FE analysis. The magnetic properties of narrow pieces corresponding to the width of the motor’s teeth and yoke were shown to be important and useful to estimating the motor iron loss more accurately.

Keywords: non-oriented electrical steel, magnetic properties, iron loss, shearing process, punching process, IPMSM

1. Introduction

There has been a growing requirement for improving a motor efficiency due to environmental issues such as global warming and energy problems. Therefore, interior permanent magnet synchronous motors (IPMSMs) have been widely used as high-efficiency motors for hybrid electric vehicles, electric vehicles, and household electrical appliances, especially in advanced products. This leads to a strong demand for further improvement of magnetic properties of non-oriented electrical steels used as the core material of various motors.

It is also important to use proper electrical steel sheets as the core material in order to improve a motor efficiency, and it is essential to predict the motor iron loss reliably at the design stage. However, manufacturing conditions such as punching, interlocking, welding, and shrink fitting are known to influence the magnetic properties of electrical steel (5–9). Since the punching and shearing give the main contribution to the deterioration of magnetic properties by manufacturing process, there has been growing interest in the influence of punching and shearing, especially in the width of the degraded region near the sheared edge where magnetic properties are affected (5–7).

Punching and shearing degrade the magnetic properties of electrical steels by plastic deformation and inducing residual stress (5). Although both the punching process simulation and magnetic field calculation have been attempted to estimate the iron loss deterioration, the relationship between the iron loss and plastic strain is based on measured iron loss data (9). Therefore, the influence of material characteristics such as the Si content, grain size, and thickness on deterioration of magnetic properties needs to be studied. In the previous works, it is reported that high Si-alloyed grade material with larger grains showed larger deterioration of the magnetic properties and that the influence of grain size was larger (2, 6). However, there has been little research on the influence of the thickness of electrical steels on the deterioration of magnetic properties.

Recently, thinner electrical steels are being widely used to realize electrical machines with high fundamental frequency due to a high pole number or high rotational speed in order to provide higher power in a constrained volume space.

The first purpose of this study is to clarify the influence of the thickness of non-oriented electrical steels on the iron loss deterioration by the shearing process in order to simulate the influence of the punching process. Electrical steels with thicknesses of 0.20–0.50 mm were used to study. Furthermore, the measured iron loss of a model IPMSM using these steels with different thicknesses and the motor iron loss calculated by FE analysis are presented in order to verify the influence of material thickness on iron loss deterioration by shearing and punching.

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2. Experimental Procedure

2.1 Variation of Material Iron Loss by Shearing Process

Non-oriented electrical steel sheets with thicknesses of 0.20–0.50 mm were investigated as shown in Table 1. The hardness and average grain size of these steel sheets, which are high Si-alloyed grade steels, were almost the same. Therefore, the effect of the thickness is evaluated properly in this study. The sheet samples were sheared into narrow pieces along both rolling direction (L direction) and perpendicular to the rolling direction (C direction) using a mechanical shear having a clearance of 15 μm. The sheared pieces were put together so that the total width was 30 mm as shown in Fig. 1. Magnetic properties were measured by Epstein test method with using the sheets of L+C direction, L direction only and C direction only.

2.2 Hardness Distribution near Sheared Edge

The specimens were prepared by the same procedure with the above-mentioned test samples. The specimens were cut into pieces and mounted in resin in order to measure the hardness of the cross section of the sheared edge. The micro-hardness (Vickers) was measured at intervals of every 40 or 50 μm inside from the sheared edge under 50 g load and 10 s holding condition. The measurements were repeated five times along perpendicular to the sheared edge.

2.3 Motor Design and Measuring Method of Segmented Model IPMSM

A model IPMSM with segmented core was designed in consideration of the commercial HEV motor. The motor topology is 12-pole/18-slot combination, and the stator winding is a conventional concentrated windings. The main specifications of the motor are listed in Table 2. Figure 2 shows a piece of the segmented stator core. The radial direction of the teeth is coincided with L direction of used steel sheets, and therefore, the circumferential direction of the yoke almost coincides with C direction. Electrical steels listed in Table 1 were used as the stator material after punching to the specified shape and size. The same rotor was used through these experiments; high Si-alloyed grade steel of 0.35 mm thickness was used as the rotor material.

The motor characteristics were measured at the rotational speed of 1000 min⁻¹ and 2.5 Nm torque, and the power output was about 260 W; this operating point in the model motor corresponds to the average operating point of JC08 mode in the referred motor. The advanced commutation angle was controlled in 15° (electrical angle). The motor iron loss was obtained from the input power, output power, copper loss and mechanical loss. The mechanical loss was measured by using a dummy rotor, in which permanent magnets were removed, as reported by Sawahata et al. (12).

2.4 Iron Loss Calculation

FE analysis was undertaken to obtain flux density waveforms in each element of the stator material by using the measured current waveforms. The total iron loss (Pt) is the sum of the hysteresis component, the classical eddy current component and the excess eddy current component due to domain wall effects, and is given by the Eq. (1) (13–15):

\[
P_t = k_h f B_{m}^2 K(B_m) + \sigma/12(d^2/T\delta_s) \int_T (dB/dt)^2 dt + (k_e/T) \int_T dB/dt |^2 dt \tag{1}
\]

where \(K(B_m) = 1 + 0.65/B_m \sum \Delta B_i\)

\(\Delta B_i\) is the variation in flux density during the excursion around a minor loop. \(B_m, f, T\) are the peak flux density, the frequency, and the electric period, respectively, and \(\sigma, \delta_s\), and \(d\) are the electrical conductivity, the mass density, and the material thickness, respectively, \(k_h\) and \(\alpha\) are hysteresis loss constants, and \(k_e\) is the excess eddy current loss constant.

The loss constants \(k_h, \alpha, k_e\) were determined by curve fitting of measured iron loss data. Iron losses due to rotational flux were calculated separately using radial and tangential flux density components, and the results were summed. This procedure has been validated experimentally (15–16).

3. Results of Iron Loss Deterioration

Figure 3 shows the influence of the sheared width on iron...
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Fig. 3. Variation of iron loss (L+C) by shearing process in material D (0.35 mm thickness)

Fig. 4. Influence of material thickness on conventional iron loss deterioration in sheared sample (L+C)

Fig. 5. Influence of material thickness on high-frequency iron loss deterioration in sheared sample (L+C)

Iron loss deterioration in material D (0.35 mm thickness). Iron loss was evaluated by conventional material iron loss $W_{15/50}$ (iron loss at 1.5 T, 50 Hz) and high-frequency material iron loss $W_{10/400}$ (iron loss at 1.0 T, 400 Hz), because the high-frequency iron loss has become more important recently, and it is reported that the efficiency and motor iron loss of a PM brushless motor have a strong correlation with $W_{10/400}$ (16). As can be seen from Fig. 3, iron loss degradation becomes much larger for the sheared width less than 15 mm, and the high-frequency iron loss is deteriorated by shearing as well as the conventional iron loss.

Figures 4 and 5 illustrate the influence of material thickness on the deterioration of conventional and high-frequency iron loss for the sheared width of 5, 10, and 15 mm, respectively. Iron loss deterioration ($\Delta W$) was defined as the increase in iron loss for a sheared 30 mm width sample (conventional Epstein sample). The deterioration in iron loss was clearly lesser in the thinner steel sheets. In order to clarify the reason, the distribution of the increase in hardness near the sheared edge was investigated as shown in Fig. 6.

It can be seen that the increase in hardness near the sheared edge is larger for thicker samples and that the distance of the increase in hardness from the edge is almost half of the sheet thickness for all tested samples. The area of the increase in hardness indicates the region of plastic deformation, and the distance of the increase in hardness from the edge is considered to reflect the region where the magnetic properties are deteriorated (17). Therefore, the thinner materials have a smaller strained area and less iron loss deterioration by the shearing process.

Figures 7 and 8 show the results of iron loss separation into hysteresis loss and eddy current loss for the sheared 5 mm width samples. Hysteresis loss was measured under 0.01 Hz, and the eddy current loss was calculated by subtracting the hysteresis loss from the iron loss. As can be seen, both hysteresis and eddy current loss were deteriorated by the shearing process, and the deterioration of eddy current loss was larger than that of hysteresis loss in 400 Hz. It is reported that the magnetic domain structure is affected beyond the region of plastic deformation due to shearing (8). The variation of magnetic domain influences excess eddy current loss. Therefore, the deterioration of eddy current loss is considered to be larger for thicker materials in high frequency.

Accordingly, the influence of the shearing process on iron loss expression is represented by the variation of loss constants $k_3$, $\alpha$, and $k_e$: this means that the classical eddy current loss is the same before and after the shearing process. Table 3
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Table 3. Variation of loss constants in material D by shearing

<table>
<thead>
<tr>
<th>Loss constant</th>
<th>Sheared 30 mm width</th>
<th>Sheared 5 mm width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_a$</td>
<td>0.0138</td>
<td>0.0203</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>1.56</td>
<td>1.43</td>
</tr>
<tr>
<td>$k_c$</td>
<td>$4.88 \times 10^{-5}$</td>
<td>$1.18 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

shows the variation of loss constants from 30 mm to 5 mm width sample by the shearing process in material D (0.35 mm thickness) as an example. Figure 9 presents the comparison of measured material iron loss and calculated iron loss by curve fitting for 30 and 5 mm width samples. As is evident from the figure, the accuracy of the fitting is almost the same for 30 and 5 mm width samples.

The above-mentioned results suggest that the application of thinner materials for the motor core may decrease the influence of the punching process on iron loss deterioration, especially for the motor with high fundamental frequency.

4. Results and Discussion of Motor Iron Loss

Figures 10 and 11 show the influence of material iron loss (30 mm width sample [L+C]) on the efficiency and iron loss of a model IPMSM, respectively. The thickness of the used material is indicated in Fig. 10. As can be seen in Fig. 10(b), the high-frequency material iron loss $W_{10/400}$ decreases as the material thickness is thinner. Therefore, the variation of $W_{10/400}$ corresponds to the change of material thickness in this study.

It can be clearly seen that the motor efficiency and the motor iron loss have a better correlation with the high-frequency material iron loss $W_{10/400}$ rather than the conventional material iron loss $W_{15/50}$ although the synchronous frequency of the motor is 100 Hz. It is previously reported that higher harmonic components are largely contained in stator flux density waveforms by applying the material DC magnetization curve of L direction to the teeth region, that of C direction to the yoke region, and that of L+C direction to the teeth tip and root region: the motor topology is shown in Fig. 2. DC magnetization curve was measured in 30 mm width sample. Then, the iron loss calculation was undertaken by applying the corresponding material properties and loss constants to the Eq. (1).

Figure 12 presents the calculated stator iron loss against the high-frequency iron loss $W_{10/400}$. As seen in the figure, the stator iron loss decreases about 0.32 W as the $W_{10/400}$ decreases by 1 W. This dependence on the $W_{10/400}$ is weaker than the dependency of the measured results shown in Fig. 11(b).

However, considering the motor dimensions presented in Table 2 and the iron loss deterioration by the shearing process described in the previous chapter, the practical iron loss of applied material is believed to be worse as compared to the iron loss of 30 mm width sample, especially for thicker materials.

Figure 13 shows the relationship between material iron loss of the sheared 10 mm width sample (L+C) and the measured motor iron loss. The motor iron loss decreased about 0.31 W.
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Fig. 13. Relationship between material iron loss of sheared 10 mm width sample (L+C) and the measured motor iron loss

\[ y = 0.31x + 2.66 \]

Fig. 14. Comparison of measured and calculated motor iron loss against material iron loss in 30 mm width sample (L+C)

as the \( W_{10/400} \) (10 mm width sample [L+C]) decreased by 1 W. This dependence on the \( W_{10/400} \) almost coincides with the calculated dependency presented in Fig. 12. Furthermore, the difference of measured and calculated motor iron loss seems to be larger as the material iron loss increases, namely, as the material thickness is thicker in this study, as shown in Fig. 14.

This can be interrupted as the difference in iron loss deterioration by the punching process for materials with different thicknesses. In other words, the deterioration of material iron loss due to punching is larger in thicker materials as exhibited in chapter 3, and therefore, the difference in \( W_{10/400} \) of 30 mm width sample does not reflect accurately the difference in iron loss of the material with narrower width. Hence, it seems to be reasonable that the dependence of the calculated motor iron loss on material iron loss in 30 mm width sample agreed well with the dependence of the measured motor iron loss on material iron loss in sheared 10 mm width sample because the teeth width of the model motor is 10 mm.

In order to confirm the above consideration, loss constants \( k_b, \alpha, \) and \( k_e \) were obtained for the sheared 5 and 10 mm width samples, and the calculation of the stator iron loss was undertaken by applying the loss constants of L direction in 10 mm width sample to the teeth region, that of C direction in 5 mm width sample to the yoke region, and that of L+C direction in 10 mm width sample to the teeth tip and root region. At first, DC magnetization curves, which were measured in 30 mm width sample, were used to obtain the flux density waveforms as well as the previous calculation, and then, DC magnetization curves of 5 and 10 mm width samples were measured, and these data were used in the next calculation.

Figure 15 illustrates the calculated stator iron loss against the material iron loss \( W_{10/400} \) (10 mm width sample [L+C]). As seen in the figure, the stator iron loss decreased about 0.37 W as the \( W_{10/400} \) decreased by 1 W. This dependence on the \( W_{10/400} \) is much larger with the measured dependency shown in Fig. 13. However, the variation of magnetization curves due to the punching process is not considered in this calculation. Punching and shearing process is also reported to influence the magnetization curve of the material(2) (3) (7).

Figure 16 shows the influence of the material iron loss \( W_{10/400} \) (10 mm width sample [L+C]) on the calculated stator iron loss with considering the effect of the punching process on both iron loss and magnetization curve. As can be seen, the stator iron loss decreased about 0.32 W as the \( W_{10/400} \) decreased by 1 W. This dependence on the \( W_{10/400} \) is almost consistent with the measured dependency presented in Fig. 13. This means that it is also important to consider the change of magnetization curve due to punching. Figure 17 demonstrates the change in magnetic flux density by the shearing process in material D (0.35 mm thickness).

Figure 18 shows the influence of material thickness on the decrease in magnetic flux density by the shearing process. The decrease in magnetic flux density was defined as the decrease in magnetic flux density for a sheared 30 mm width sample. It can be clearly seen that the decrease in magnetic flux density is larger in lower magnetic field strength.
and thicker materials. It is considered that these variations affected the above calculation results of the stator iron loss.

The above discussion is based on the experimental results of 2.5 Nm torque at the rotational speed of 1000 min⁻¹, and the influence of the motor speed and output torque is considered as follows. The fraction of motor iron loss for all motor losses increases as the motor speed increases. Therefore, in this case, the influence of material iron loss, viz. material thickness, on the motor iron loss becomes larger, and the dependence on \( W_{10/400} \) of motor iron loss as shown in Figs. 12, 13 etc. becomes much stronger. The fraction of motor iron loss decreases as the output torque increases because the copper loss increases. However, the influence of material iron loss, viz. material thickness, on the motor iron loss is also considered to become stronger because the higher harmonics generated by armature reaction become larger \((16)(19)\).

Table 4 summarizes the calculation conditions of stator iron loss based on FE analysis. Finally, in order to compare the calculated motor iron loss with the measured motor iron loss, we have considered the rotor iron loss. Rotor iron loss in IPMSM is reportedly about less than 10% of the motor iron loss in the same stator and rotor material, and most of the rotor iron loss is the eddy current loss and the hysteresis loss is negligible \((21)\). Then, the classical and excess eddy current losses were calculated by using the Eq. (1), and the results were about 0.5 W.

Figure 19 summarizes the calculated and measured motor iron losses. The difference between the measured and calculated iron losses was clearly larger for thicker materials under the No. 1 and No. 2 conditions because iron loss deterioration by the punching process was not considered in the No. 1 condition, and the variation of magnetization curve by the punching process was not considered in the No. 2 condition. The calculated iron loss under the No. 3 condition agreed well with the measured motor iron loss because the iron loss deterioration and change in magnetic flux density due to the punching process were both considered.

Consequently, magnetic properties, viz. iron loss and magnetization curve, in narrow samples corresponding to the width of the motor’s teeth and yoke are necessary for accurate estimation of the motor iron loss.

### 5. Conclusion

The influence of the shearing process on iron loss deterioration in non-oriented electrical steels with different thicknesses has been investigated. The iron loss deterioration was larger in thicker steel sheets, and the deterioration of eddy current loss was larger for thicker materials in high frequency.

From the evaluation of material and motor iron loss, the application of thinner steel sheets for the motor core is thought to decrease the influence of the punching process on iron loss deterioration. The magnetic properties including the magnetization curve for narrow pieces corresponding to the width of the motor’s teeth and yoke are essential for estimating the motor iron loss more precisely.

### References

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