Factors related to interlocking, which is known to affect the core magnetic properties of motors and generators, were analyzed with the aim of achieving greater accuracy in the prediction of core losses. In a ring core sample assembled by V-type interlocking, dowel formation and dowel jointing showed comparable contributions to iron loss increase at low frequencies (e.g., 50 Hz), whereas at high frequencies, increases in iron loss due to dowel jointing were greater than those due to dowel formation. It was suggested that dowel formation increased iron loss because of the strains originating from the plastic constraint due to the existence of dowels. Jointing of individual dowels increased eddy current loss at higher frequencies (e.g., 400 Hz). Furthermore, eddy current loss increased significantly under the existence of an interlinkage magnetic flux across the line between two adjacent dowels, including the case of staggered dowel arrangements. The increase in iron loss in a motor core owing to interlocking can be estimated by the obtained degradation tendencies of iron losses in ring cores with respect to the density of interlocking dowels.

Keywords: interlocking, motor, generator, non-oriented electrical steel, core loss, iron loss, flux density

1. Introduction

Interlocking is a commonly used method in automated fabrication of motor and generator cores. In this method, dowels are formed in an early stage of the die stamping system, and are then jointed to each other so that the stamped sheets form a combined lamination. Despite the industrial usefulness of this technique, interlocking is known to deteriorate the magnetic properties of cores (1). In the past, studies on the influence of interlocking on core magnetic properties were limited compared to those on punching. Moreover, previous studies focused mainly on the tendency of interlocking in degrading magnetic properties.

Based on the consideration of the interlocking processes, the reasons for the deterioration of core magnetic properties are inferred to be as follows. Strains are introduced during dowel formation and jointing of dowels. From previous knowledge, punching introduces plastic and elastic strains around the worked edges (2), and additional elastic strain is introduced during jointing in order to combine the laminations. Formation of short circuits can also be a reason for the deterioration of core loss. Kaido et al. theoretically discussed the effect of short circuits related to interlocking (3), but did not present measured iron losses. Kurosaki et al. evaluated the influence of interlocking and welding on iron loss when short circuits were introduced in the core, and concluded that the effect of welding was large (4). In their study, the increase of iron loss due to interlocking was small because loss was not evaluated at higher frequencies than 50 Hz. Despite these former studies, an inclusive and quantitative analysis of the factors responsible for the degradation because of interlocking is still lacking. Moreover, high frequency iron loss is an increasingly important issue because recent motors, such as the BLDC (Brushless DC) motor and the SR (Switched Reluctance) motor, demand reduction of iron loss at high frequencies (e.g., 400 Hz) to improve their efficiency (5–7) compared to conventional induction motors. Therefore, we focused on the influence of interlocking on high frequency iron loss.

The purpose of this study is to clarify the influence of various factors on core magnetic properties in order to improve prediction accuracy of motor core loss.

2. Experimental Method

Ring core samples with the different interlocking configurations shown in Fig. 1 were made from non-oriented electrical steel sheet (35JNE250) with a thickness of 0.35 mm in order to study the influence of interlocking in an ideal magnetizing condition. The outer and inner diameters of the ring core were 55 mm and 35 mm, respectively. V-type interlocking dowels with a length of 3 mm in the circumferential direction, a width of 1 mm in the radial direction and a depth of 0.25 mm (70% of the sheet thickness) were formed simultaneously with the punching of the ring shape. The dowel configurations in Fig. 1 were chosen in order to evaluate the effect of the number and location of the dowels. In cores T and U, the dowels were placed at the center of the magnetic path. The dowels in cores V, W, and X, were placed 2.5 mm from the outer or inner edges, as shown in Fig. 1. Note that core W has a staggered dowel configuration. The convex and concave parts of dowels were jointed to each other so that the punched cores formed a combined lamination by using a tool that was different from the punching
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The pressure applied to the cores for jointing was 3.5 MPa.

In core TH, holes having the same dimensions (3 mm × 1 mm) and a configuration similar to the dowels of core T, were blanked using the same punches for dowel formation in order to investigate the effect of dowels in comparison to holes.

The annealing was applied at 750°C for 3 h in an Argon atmosphere intending to eliminate the plastic strain of the laminated core. Grain growth due to annealing is negligible in this grade of material. After annealing, elastic strain to combine the laminations remains in the cores.

The dowel configurations and core types shown in Table 1 were prepared by the procedure outlined above. In Table 1, the cores after jointing are numbered using the number 2, and the cores after annealing are numbered with number 3. Specifically, in the core type T, the core magnetic properties were measured before jointing (T1 in Table 1). The total core height of all ring core samples was 4.9 mm (14 laminations).

The increments of iron loss elicited by the fabrication of the ring cores include the following causes:

1. Strains introduced by core shape punching
2. Strains introduced by dowel formation
3. Strains introduced by jointing of dowels
4. Strains remaining after annealing due to jointing
5. Influence of holes in the case of core TH
6. Additional eddy current loss due to short circuits between dowels (herein, this loss is defined as “extra loss”).

The loss increase in core T2 with respect to core S3 elicited as a result of each of the aforementioned factors (1)–(5) are denoted by P, D, J, J’, and H, respectively. The deterioration due to residual strains after annealing (J’) is distinguished from that before annealing (J) because the strains due to jointing after the annealing could be different from that before annealing. Extra loss (6) is the additional increment in cores U, V, W, and X, by adding extra three dowels to core T, other than the loss increases due to the strain denoted by P, D, J, and J’. This component mainly originates from the eddy current between interlockings. Estimated iron loss deteriorations with respect to core S3 are shown in square brackets in Table 1. These will be discussed in a latter section.

The magnetic properties of these cores were measured under an AC magnetization condition with 100 turns of primary winding and 100 turns of secondary winding. Loss at 400 Hz was separated into a hysteresis loss and an eddy current loss using the loss values at 50 Hz and 400 Hz, assuming that the hysteresis loss is proportional to the frequency, and that the eddy current loss is proportional to the square of the frequency.

The plastic strains introduced around the dowels were measured by a micro Vickers hardness test with a 50 g load applied from the cross-section of the dowels, as shown in Fig. 2. Hardness was evaluated by the increment ratio with respect to the hardness of the material without strain.

### Results and Discussion

#### 3.1 Strain Distribution and Magnetic Properties

The distribution of hardness around a dowel is shown in Fig. 2. An increase in hardness was observed in the vicinity of the strongly deformed area around the dowel. Herein, the increases in hardness were caused by the accumulation...
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The width of the area where the increase in hardness was observed in the vicinity of the dowel edge L in Fig. 2(b) (outwards from the edge) was approximately 0.15 mm, and was almost the same as that around a sheared edge (3). This is reasonable because the type of the work applied to edge L is shearing.

The peak flux densities and iron losses measured at 50 Hz were compared among the cores without dowels (S1), with holes (TH), with dowels before jointing (T1), and the core after jointing (T2). The results are shown in Figs. 3 and 4.

In Fig. 3, the flux densities of core T1 with dowels were lower than that of core TH with holes at weaker magnetic fields than 300 A/m. In Fig. 4, the loss of core T1 was larger than that of core TH at \( B_m = 1.0 \) T and \( f = 50 \) Hz. These results indicate that at low flux densities, formation of dowels deteriorates core magnetic properties more than making holes. In contrast, at 1.5 T, the iron loss of core T1 was comparable with that of TH in Fig. 4(b), and the flux density of core T1 was almost the same as that of core TH at approximately \( H = 1800 \) A/m in Fig. 3. This can be explained by the inferior permeability of core TH (with holes) at a higher flux density due to the absence of magnetic material inside the holes. At \( H = 5000 \) A/m, core TH yielded the minimum flux density.
density.

The core after jointing (T2) yielded the lowest flux density at the magnetic field strengths lower than 1000 A/m, and T2 yielded the highest iron losses at both flux densities of 1.0 T and 1.5 T.

The distribution of plastic strains around the holes in core TH is regarded to be the same as that for the dowels in core T1 because the shearing work is the same between the dowel formation and blanking. In addition, the permeability in the area corresponding to the dowels is worse in core TH than in core T1. However, the deterioration of the magnetic properties at lower flux densities was significant in core T1. These facts imply that the plastic constraint due to the existence of dowels induces elastic strains spreading over a wide area inside the core. Moreover, jointing adds extra strains to the cores, further deteriorating its magnetic properties. Furthermore, this strain is presumed to be heavier than that elicited by the formation of dowels because the deterioration occurs in the high-flux density region.

Figure 5 shows a comparison of the iron losses of jointed cores with different dowel configurations at 50 Hz. In Fig. 6, iron losses at 400 Hz and loss components of annealed and non-annealed cores are also shown. The ratios of iron losses to core S1 are also indicated in these figures.

From the collected data, it is clear that increasing the number of dowels also increases iron loss. In Fig. 5, the iron loss ratios with respect to core S1 at 1.0 T were larger than at 1.5 T. This indicates that the deteriorations of the magnetic properties by interlocking are significant in low-flux density regions.

When Fig. 5(a) and Fig. 6(a) are compared, it is obvious that the iron loss ratios to core S1 were almost the same at 50 Hz and 400 Hz in T2 and U2. However, the ratios of V2, W2, and X2 were significantly larger at 400 Hz than at 50 Hz.

The increased losses in cores V2, W2, and X2 are presumed to be due to increased eddy current loss. The common feature of cores V, W, and X, is that the dowels are not aligned in the center of the cores width, but they are rather located on the inner or outer sides inside the magnetic path. It is inferred that the increases in iron loss in these cores at higher frequencies is due to the effect of eddy current loss induced by short circuits between the dowels. This additional eddy current loss is defined as “extra loss”, as mentioned in Sect. 2.

3.2 Analysis of Iron Loss It has been shown that the deterioration of the core magnetic properties due to interlocking originates from several factors based on its fabrication process. The increment of iron loss comprises increases in the hysteresis loss, the eddy current loss, and the extra loss.

The causes of the deterioration in core magnetic properties can be summarized by items (1) to (6), as mentioned in Sect. 2. The amounts of deterioration due to each manufacturing step were estimated from the measured results assuming that the interaction effects between the factors are negligible.

As mentioned in Sect. 2, the values of the deterioration in core T2 because of each factor related to the core fabrication with respect to S3 are denoted by P, D, J, and J’.

When additional three or six dowels were added to core T in the case of cores U, V, W, and X, the extra loss occurred owing to increased eddy current loss. This loss is denoted by $E_U$, $E_v$, $E_W$ and $E_X$ for core types U, V, W, and X, respectively.

If we assume that no interaction effect exists between these factors, the contributions of these factors to the loss of each core can be expressed by the formulae shown in square brackets in Table 1. The estimated loss deterioration for core V2, for example, is explained as follows: the deterioration in core V2 due to punching is assumed to be the same as that in cores S1 and T2, which is denoted by P. Core V2 has twice as many dowels as core T2, and the deterioration by the strain induced by the dowel formation and jointing is thus two times higher than that of core T2. When the extra loss in V2 and V3 is defined by $E_V$, the amount of loss deterioration in core V2 compared to S3 can be expressed as $P+2D+2J+E_V$, as shown in Table 1. After the annealing, the influence of strains introduced by punching and dowel formation disappears. If the loss increase in core T3 due to the residual strains induced by jointing after annealing is defined by $J’$, the amount of loss deterioration in core V3, which has twice as many dowels as those for T3, is expressed by $2J’+E_V$. Herein, extra losses before and after annealing are assumed to be the same because short circuits at interlocking points do not presumably change by annealing.

Components of iron loss deterioration related to punching and interlocking, such as $P$, $D$, $J$, and $E_U–E_W$ were derived using the formulae shown in the square brackets in Table 1. For example, the loss component $J$ can be derived by subtracting the loss of core T1 from core T2. The ratios of iron loss increment to core S3 defined in the following formula (1) are shown in Fig. 7 for factors $P$, $D$, $J$, and $E_U–E_X$.

\[
\text{Ratio of loss increment [%]} = \frac{\text{Loss increment in factor X with respect to core S3}}{\text{Iron loss of core S3}} \times 100
\]  

\[\text{--------------- (1)}\]
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Fig. 7. Ratio of increment in iron loss due to each factor related to punching and interlocking

Herein, factor X represents P, D, J and E_{U\text{--}EX} in units of W/kg.

The increments of hysteresis loss and eddy current loss due to each factor were calculated based on the loss estimation in Table 1 at 1.0 T and 400 Hz. The ratio of each loss with respect to the total iron loss of core S3 was defined using formula (1). The results are shown in Fig. 8.

In Fig. 7, the total amount of deterioration by interlocking in core T2, which is the sum of D and J, is larger than that by punching. The ratio of the iron loss increment due to dowel formation (D) decreased with increasing frequency. On the other hand, the ratio due to jointing (J) did not depend on the frequency. As shown in Fig. 8, jointing and punching increased eddy current loss more than the formation of dowels. It is inferred that the strains induced by punching around the edges of the outer and inner outline enhance the flux wave distortion at high frequencies at which the flux concentrates near the surface, resulting in the increase in eddy current loss. A similar reason can be expected for the loss increase in the loss due to the jointing of dowels.

Since the increase in eddy current loss in cores T3 and U3 relative to core S3 were small, as shown in Fig. 6(b), it is concluded that the contribution of the eddy current induced around individual dowel after jointing is negligible. Formation of dowels mainly increased hysteresis loss, which is caused by the plastic and elastic strains induced around the dowels, as assumed in the previous section.

Although the extra loss E_{U} in core U was small, E_{V} in core V and E_{W} in core W were significantly larger. This means that the additional eddy current loss increased in the cores that had interlinkage magnetic flux components across the line between the two adjacent dowels (core V: a-b, c-d, e-f; core X: a-b, c-d, e-f, g-h, i-j, k-l, as shown in Fig. 1). Core W that had a staggered dowel arrangement showed high extra loss comparable to that of core V. In core W, it was assumed that short circuits between the dowels (core W: a-b, b-c, c-d, d-e, e-f, f-a, as shown in Fig. 1) induced eddy currents that led iron loss increases.

3.3 Application to Motor Core Loss Estimation

It has been shown that the increase in hysteresis loss and eddy current loss due to interlocking originates from the strains due to dowel formation and jointing. The additional eddy current loss (extra loss) is enhanced by the formation of the eddy current path between the interlocking points that have interlinkage magnetic flux components. These phenomena also occur in actual motor cores, however, interlocking-related factors were not previously considered in the iron loss estimation for motor cores because the degradation factors were not clearly understood. Hereafter, the way to estimate iron loss increase in motor cores is described using the results obtained in this work.

Figure 9 shows the effect of dowel density on hysteresis loss of ring cores. Herein, the dowel density refers to the number of dowels in 100 mm² of a ring core area. In this figure, the hysteresis loss increases linearly with dowel density. The difference between the non-annealed and annealed cores originates from the relieved stress around the interlocking and punched edge.

For the motor core that has the same interlocking type and dimension as that of the ring core used in this study, the increment of the hysteresis loss in a certain portion of the motor core due to interlocking can be estimated from the data shown in Fig. 9 through consideration of the density of the dowel. The localized influence of the interlocking around the dowels is translated to a homogeneous deterioration over the core’s portion. A similar method was used in the analysis of the punching stress(7).

Subsequently, the increase in eddy current loss due to interlocking was analyzed. Figure 10 shows the effect of the dowel density on eddy current loss among cores S, T, and U, before and after annealing. These cores do not have interlocking pairs composing interlinkage flux component...
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Fig. 10. Effect of dowel density on eddy current loss of ring cores

Fig. 11. Effect of the density of the interlocking pair on the extra loss of annealed ring cores

between the dowels. In Fig. 10, the eddy current loss of the non-annealed core increased linearly with the dowel density. However, no increase of eddy current loss appeared in annealed cores. The increased eddy current loss in the non-annealed core is expected to originate from strains around dowels, which enhances the distortion of the flux waveform. Since most of the strains, except the elastic strain for fixation, are eliminated in annealed cores, the flux waveform distortion that increases the eddy current loss is suppressed.

The result shown in Fig. 10 can be applied to the eddy current loss estimation of the motor core in a similar way to the hysteresis loss analysis mentioned above.

The extra loss occurs in the interlocking pair when they have interlinkage flux components between the pair. The effect of the density of the interlocking pair on the extra loss is shown in Fig. 11 based on the results of the annealed cores. Herein, the interlocking pair is defined as the adjacent set of dowels. In cores V and X, the numbers of the interlocking pair are three and six, respectively. The densities of the interlocking pair are derived by dividing these numbers with the area of the ring core. As shown in Fig. 11, the extra loss showed a linear and significant increase with the density of the interlocking pair. This indicates that the additional eddy current loss was mainly induced between the nearest interlocking neighbors. Core W3 that has a staggered dowel configuration is concluded to have three interlocking pairs (density of 0.21/mm²) based on the relation of Fig. 11.

When the measured iron loss increment in the motor core due to interlocking exceeds the value estimated from the results in Figs. 9 and 10, the core loss is possibly affected by the extra loss shown in Fig. 11.

In Figs. 9–11, the tendency of loss deterioration with parameters, such as the dowel density and the density of the interlocking pair, are presented in the case of a specific interlocking specification. Motor core losses can be roughly estimated by referencing these values related to interlocking. In contrast, for the core loss estimation applicable to a general interlocking specification, the local loss distributions caused by the plastic and elastic strains and the eddy current should be studied around the dowels. FEM analysis of strain and loss distribution around the dowels is effective for general and precise loss evaluation. The proposed method in this paper for analyzing the interlocking-related loss origins using a simple ring core can contribute to the verification of the validity of the results of the numerical core-loss simulation.

4. Conclusion

The factors of degradation in core magnetic properties caused by interlocking were analyzed. Formation of dowels and jointing showed comparable contributions to iron loss increases at low frequencies, such as 50 Hz, while at high frequencies, the increases in iron losses due to jointing were larger than those due to formation of dowels. From the comparison between the core with dowel and the core with holes, the formation of dowels is suggested to increase the iron loss by the strain that originated owing to the plastic constraint, as a result of the existence of the dowels. When the dowels were positioned so that the connecting line between the two dowels had a linkage flux, an additional eddy current occurred between the dowels causing a significant increase in iron loss at high frequencies.

This work has shown that the consideration of the introduction of strains and the formation of the eddy current paths due to interlocking is important for improving the core loss. In particular, in order to prevent the degradation of iron loss at high frequencies, such as 400 Hz, that influences the efficiency of BLDC and SR motors, the locations of the dowels should be selected in such a way to avoid the formation of additional eddy current paths by short circuits at interlocking points even when dowels are arranged at remote positions.

The relation between the hysteresis and eddy current losses and the dowel density, and the relation between the additional eddy current loss and the density of the interlocking pair, have been studied quantitatively in the ring core with interlocking. Applying these results to the motor core can contribute to the improvement in the accuracy of the motor core-loss evaluation.

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