Influence of Interlocking on Magnetic Properties of Stacked Core

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Abstract:

Factors for interlocking, such as formation of dowels, jointing between dowels, and the formation of short circuits were analyzed from the viewpoint of core magnetic properties by using ring cores with interlockings. Formation of dowels had greater influence on the deterioration of the magnetic properties than making holes of the same size, and the jointing of dowels added additional deteriorations. These adverse effects were enhanced at higher magnetizing frequencies. The effect of individual interlocking on the eddy current loss was small, however, formation of eddy current paths causes extra eddy current losses. Finally, increase in hysteresis loss and eddy current loss with the number of dowels and the pairs of dowels were analyzed for the basic knowledge of core loss estimation.

1. Introduction

Interlocking is an industrial manufacturing process for motor and transformer cores, in which stacked cores are produced by punching electrical steel sheets to the shape required in the core, following by jointing the punched sheets to form a combined lamination. In the in-die interlocking method which generally used in this process, the punching die include a mechanism that performs interlocking, and forms protrusions called "dowels" on an electrical steel sheet before it is punched by the die. Next, the electrical steel sheet including the formed dowels is punched to the core shape by the die punch, and the dowels are jointed using the stroke of the punch descending in the die. This process is performed repeated, continuously forming a stacked core, as shown in **Figure 1**.

Although the interlocking method described above offers excellent productivity, it is known that the magnetic properties of electrical steel sheets are deteriorated by this process[1–3], but a detailed knowledge of the factors responsible for deterioration was still lacking. Therefore, the purpose of this research was to elucidate the factors in deterioration of magnetic properties due to interlocking in order to contribute to preventing degradation of core properties and improving the accuracies of predictions of the amount of deterioration. Here, the deterioration factors were divided three types, i.e., strains introduced by dowel formation, strains due to jointing between dowels, and electrical short circuiting between dowels, and deterioration behavior due to interlocking was investigated and analyzed[4,5].

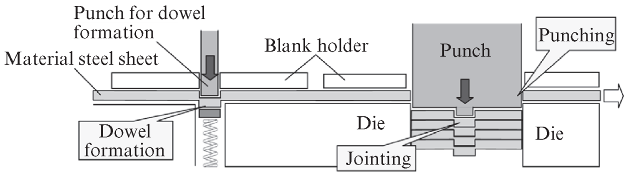

Fig. 1 Schematic view of interlocking using progressive die

2. Experimental Method

The effects of interlocking on the magnetic properties of cores were evaluated in order to analyze the factors in deterioration. To conduct the evaluation under the ideal magnetization conditions, in this research, magnetic properties were investigated using ring-shaped test specimens (hereinafter called "ring cores" or simply "cores"), as shown in **Fig. 2**, which were prepared by interlocking.

As the dimensions of the ring cores, the outer diameter was 55 mm, the inner diameter was 35 mm and the stacked height was 4.9 mm (sheet thickness:

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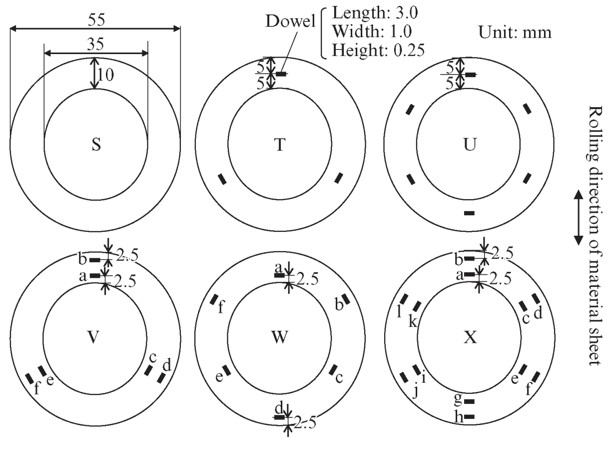

Fig. 2 Ring core samples and positions of interlocking dowels

0.35 mm×14 laminated sheets). V-type interlocking was performed. When seen from above, the dowel length and width were 3 mm and 1 mm, respectively, and the dowel height (height of dowel protrusion from the sheet bottom surface) was 0.25 mm, which was equal to 70% of the sheet thickness. The electrical steel sheet used as the base material was the non-oriented electrical steel 35JNE250 (sheet thickness: 0.35 mm) manufactured by JFE Steel.

A simple die (single operation die) was used as the punching die in fabrication of the ring cores with interlocks for this test. First, the interlocking dowels were formed simultaneously with punching of the inner and outer circumference of the ring shapes, and unjointed component core pieces were obtained. Next, these unjointed core pieces were placed one by one in a jointing jig, the concave and convex parts of dowels were fitted into each other, and the punched cores were formed into a combined lamination under a jointing pressure of 3.5 MPa. In this process, the dowel parts of the topmost core piece were pressed by protrusions of the same shape as the dowels, which were provided on the jointing jig, and the top sheet was jointed to the partially complete stacked core which had already been jointed so as to form a combined lamination. Since the inner and outer circumference parts fabricated by this method were punched, the unannealed cores contained not only strain due to interlocking, but also punching strain in the region near the inner and outer circumferences of the cores.

In addition, in order to investigate the effect of dowel formation, core (core TH) was also prepared by punching holes having the same dimensions (3 mm×1 mm) and configuration as the dowels of core T.

Strain relief annealing of some cores was performed at 750°C for 3 h in an Ar atmosphere to evaluate the magnetic properties after eliminating plastic strain. Because high grade electrical steel sheets were used as the material in this research, it was possible to remove only plastic strain with negligible grain growth due to annealing under the above-mentioned conditions. Since the interlocked cores were in the same jointed condition after annealing, the stress introduced by jointing remained in the cores.

The ring core samples fabricated by the method described above were designated S, T, U, V, W and X, as shown in Fig. 2. The number 1 was added to indicate a core before jointing (e.g., T1), 2 was added to indicate a core after jointing (T2), and 3 was added to indicate a core after strain relief annealing.

The increments of iron loss in the ring cores due to interlocking and punching were classified and analyzed by the following causes (1) to (6). The amount of deterioration of iron loss in core T2 or core TH with respect to core S3 (strain relief annealed core) for each of these deterioration factors is denoted by the symbols in shown in parentheses ( ).

(1) strains introduced by core shape (outer circumference) punching (P)
(2) strains introduced by dowel formation (D)
(3) strains introduced by jointing the dowels (J)
(4) strains due to jointing dowels remaining after strain relief annealing (J')
(5) strains due to holes having the same dimensions as the dowels (H)
(6) additional eddy current loss due to short circuit by interlocking (E_U, E_V, E_W, E_X)

In the following, the increment of iron loss due to additional eddy current loss caused by short circuit between interlocking points (dowels) is called “extra loss.” The number of dowels in cores U, V, W and X with respect to T2 is n times (for U, V and W, n = 2, and for X, n = 4). Therefore, if the effects of D and J (or J') are included, the increment of iron loss with respect to core S3 is equal to $P+nD+nJ$ (or nJ'). Assuming the additional increase in iron loss in comparison with these values is defined as extra loss, the extra loss of cores U, V, W and X is denoted as E_U, E_V, E_W and E_X, respectively.

In the term for deterioration of iron loss due to dowel jointing (J), the increment of iron loss due to strains remaining after strain relief annealing (J') is distinguished from J because it is conceivable that the amount of strain remaining after strain relief annealing may be different from amount introduced by dowel jointing. The strains accompanying dowel jointing include plastic strain introduced by jointing dowels and jointing stress due to jointing of the adjacent stacked steel sheets. It is thought that plastic strain is released

Table 1 Tested ring cores (estimated increase of core loss)

Core conditions \ Symbols / Dowels	S	T	U	V	W	X
		Dowel configurations				
	No dowel	1×3	1×6	2×3	1×6 (Staggered)	2×6
With holes	—	TH [P+H]	—	—	—	—
Before jointing	S1 [P]	T1 [P+D]	—	—	—	—
After jointing	—	T2 [P+D+J]	U2 [P+2D+2J+E_U]	V2 [P+2D+2J+E_V]	W2 [P+2D+2J+E_W]	X2 [P+4D+4J+E_X]
After annealing	S3 [−]	T3 [J']	U3 [2J'+E_U]	V3 [2J'+E_V]	W3 [2J'+E_W]	X3 [4J'+E_X]

[ ] indicates estimated increase of core loss in each core. The following values P, D, J, J', H are the amount of deterioration by each factor defined in core T with respect to core S3. E_U, E_V, E_W, E_X represent extra loss due to increased eddy current loss in core U, V, W, X, respectively. P: punching strain, D: strains introduced by dowel formation, J: strains introduced by jointing (before annealing) , J': strains introduced by jointing (after annealing) , H: formation of holes.

after strain relief annealing, and jointing stress remains.

Table 1 shows the increase of iron loss of each of the cores shown in Fig. 2 in comparison with core S3, using the iron loss increase factors P, D and J of core T2 and the extra iron losses E_U, E_V, E_W and E_X of cores U, V, W and X. Here, assuming hypothetically that there is no interaction, *etc*. between the iron loss factors, iron loss other than extra loss was obtained as the increment of iron loss proportional to the number of dowels.

The magnetic properties of the ring cores were evaluated under AC magnetization by a primary coil with 100 turns of winding, and were detected by a secondary coil having 100 turns of winding. Iron loss measurements were conducted at the frequencies of 50 Hz, 400 Hz and 1 kHz, and iron loss was calculated by the wattmeter method. Among the component elements of iron loss, eddy current loss and hysteresis loss were calculated by the two frequency separation method from the iron losses at 400 Hz and 50 Hz for the case of magnetization at the frequency of 400 Hz, assuming that hysteresis loss is proportional to the frequency and eddy current loss is proportional to the square of the frequency.

The accumulation of plastic strains around the dowels was evaluated by the increment of hardness. Here, the distribution of hardness under a 50 g load was measured with a micro Vickers hardness tester, and the amount of strain accumulation was investigated by using the increment ratio of hardness with respect to the hardness without strain due to working.

3. Experimental Results and Discussion

The distribution of the hardness increment ratio around a dowel (center-of-sheet thickness position) is shown in **Fig. 3**. Core T1 before jointing was used as the sample for this hardness measurement. From these results, increased hardness can be observed in parts that were strongly deformed by dowel formation. This type of hardness increase is caused by the accumulation of plastic strains. In Fig. 3, the width (one side) of the hardness increase region around the dowel edge L is about 0.15 mm. Thus, the width of the hardness increase region due to punching strain is equivalent to the long-known value of approximately 1/2 of the sheet thickness[6].

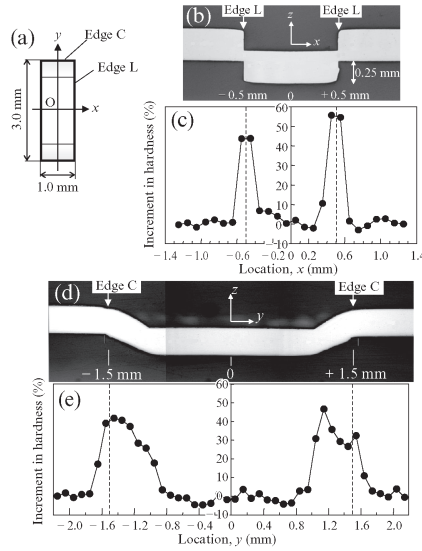

Fig. 3 Cross sectional view of dowel and hardness distribution inside and around dowel

Figure 4 shows the relationship between the maximum value of the magnetic field strength measured under the AC magnetization of 50 Hz and the magnetic flux density of the core without dowels (S1), the core with holes (TH), the core with dowels before jointing (T1) and the core after jointing (T2). **Figure 5** shows the results of a comparison of the magnetic loss of these cores under AC magnetization at 50 Hz.

As shown in Fig. 4, at magnetic field strengths of 300 A/m or less, the magnetic flux density of core T1 with dowels (before jointing) is lower than that of the core with holes TH. Furthermore, as shown in Fig. 5, the iron loss of core T1 under AC magnetization at the maximum magnetic flux density of 1.0 T and frequency of 50 Hz is higher than that of core TH. Based on these results, it can be concluded that dowel formation has a more pronounced effect in degradation of magnetic properties than hole-making in the low flux density region. However, under AC magnetization at 1.5 T, cores T1 and TH displayed almost identical iron loss. As shown in Fig. 4, the flux densities of core T1 and core TH are substantially the same at the peak intensity of the magnetic field H = 300 to 1 000 A/m, but core TH showed the lowest flux density at H = 5 000 A/m. As the reason for this decrease in the magnetic properties of core TH in the high flux density region, due to the absence of magnetic material in the holes, magnetic poles form on the inner side of the holes when the core is magnetized, and this reduces the magnetization of the magnetic material of the core.

Among the cores compared here, core T2 after jointing displayed the lowest flux density at magnetic field strengths of less than 1 500 A/m and the highest iron loss at both the maximum flux densities of 1.0 T and 1.5 T.

At the dowel edge L in Fig. 3, it is thought that the distribution of plastic strain around the dowels in cores T1 and T2 and holes in core TH is almost the same because similar shearing work was performed in dowel formation in cores T1 and T2 and in hole-making in core TH, and furthermore, because there is no magnetic material in the holes in core TH, this should be a disadvantage in terms of magnetization. However, notwithstanding this, the magnetic properties of core T1 were inferior to those of core TH in the low flux density region. This is estimated to be an effect of the spread of the elastic strain region to a wide area because the plastic deformation associated with the formation of dowels in T1 constrains the area surrounding the dowels, core T2 also displays a further deterioration of magnetic properties due to the additional strain introduced by jointing of the dowels.

Figure 6 shows the amount of change in the measured flux density and iron loss before jointing, after jointing and after separating the once-jointed core using a core that was the same as core T2. In this figure, an increase is shown as positive. AC magnetization (frequency: 50 Hz) was used as the magnetization condition, and the standard for calculating the amount of change is core S1 (simple ring core without dowels after punching).

As shown in Fig. 6, the magnetic properties of the core after jointing was removed and the core was separated were more favorable than those of the core after jointing. This indicates that degradation of the magnetic properties of the core was caused by the jointing strain introduced when the pairs of core pieces were joined, and conversely, magnetic properties were improved by releasing the jointing strain by releasing the jointing condition (separating the core). However, as also shown in Fig. 6, the magnetic properties of the

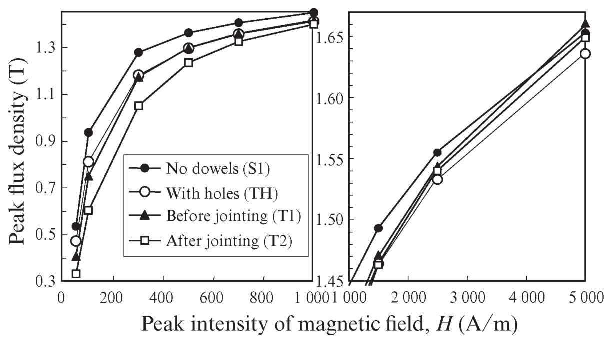

Fig. 4 Variation of peak flux densities in cores with different dowel conditions

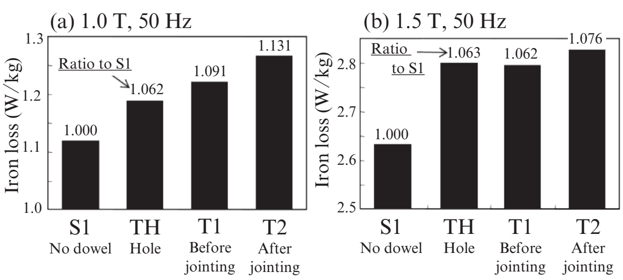

Fig. 5 Comparison of iron losses of cores with interlocking

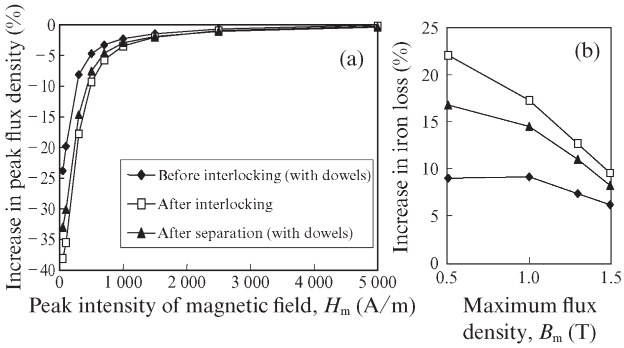

Fig. 6 Comparison of increase in flux density and iron loss between core before jointing, after jointing, and after separation

core after separation were inferior to those of the core before jointing, suggesting that deterioration of iron loss was caused not only by the jointing strain due to joining pairs of core parts, but also by the introduction of plastic strain.

Figure 7 shows a comparison of the magnetic properties of interlocked cores with different dowel configurations before strain relief annealing under a magnetizing frequency of 50 Hz (B_m = 1.0 t, 1.5 T), and **Fig. 8** shows the iron loss of the cores before and after annealing, together with the breakdown of iron loss into hysteresis loss and eddy current loss under a magnetizing frequency of 400 Hz. Fig. 7 and Fig. 8 show the ratio of iron loss to that of cores without dowels (S1 or S3). According to these results, iron loss increases as the number of dowels in the core increases, clearly indicating that interlocking deteriorates magnetic properties. The ratio of iron loss to that of core S1 in Fig. 7 is larger at B_m = 1.0 T than at 1.5 T. As also shown in Fig. 4 and Fig. 5, this corresponds to the fact that the deterioration of iron loss by interlocking is remarkable in the low magnetic flux density region. Comparing the ratio of iron loss with respect to the standard core (S1) in Fig. 7 (a) and Fig. 8 (a), the ratio of iron loss of cores T2 and U2 is almost the same at the both magnetizing frequencies (50 Hz, 400 Hz), but the ratio of iron loss of cores V2, W2 and X2 at 400 Hz increases remarkably in comparison with the iron loss at 50 Hz. The common feature of cores V2, W2 and X2 is the arrangement of dowels either at the inner side or outer side of the center of width of the ring core, and not at the center of the magnetic path. This suggests that the increase in the iron loss observed in cores V2, W2 and X2 can be explained by the formation of electrical closed circuits by short circuiting, which occurs at the dowel positions between the adjoining stacked steel sheets in the stacking direction, and the eddy currents (extra loss) induced by the AC magnetic flux interlinked with this.

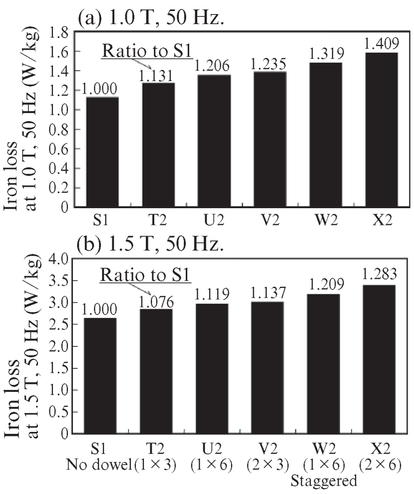

Fig. 7 Iron losses of cores with different interlocking configuration before annealing

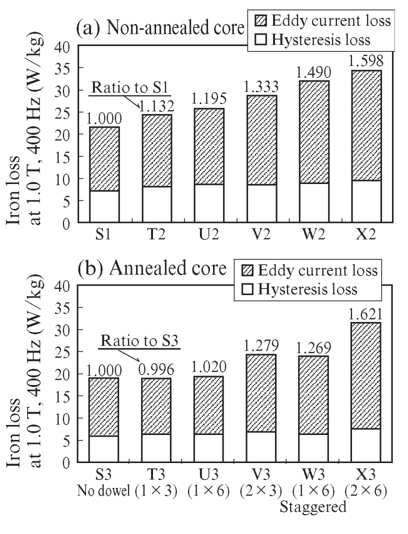

Fig. 8 Comparison of iron loss component at 1.0 T, 400 Hz in different interlocking configuration

4. Analysis of Iron Loss

From this point, we will describe an attempt to separate and evaluate the factors in degradation of magnetic properties by interlocking.

The factors in iron loss in the ring core fabrication process are considered to be the factors (1) to (6) in Chapter 2. On the assumption that no interactions occur between deterioration factors related to the fabrication process, their contributions to the iron loss in the respective cores (with respect to core S3, in which no strain exists) can be expressed by the formulae shown in the brackets [ ] in Table 1, and the degradation of magnetic properties by individual interlocking factors can be treated additively, as in a first approximation[4)].

Based on the above-mentioned assumptions, the increment of iron loss in the cores can be calculated by using the iron loss factors P, D and J defined by core T2, J' defined by core T3, and E_U, E_V, E_W and E_X defined by cores U, V, W and X. For example, in the case of core V2, the iron loss due to punching strain is the same as in core T2, which is denoted by P, but because the number of dowels of core V2 (6 dowels) is twice as large as that of core T2, the iron loss due to dowel formation is $2D$. Similarly, the deterioration due to dowel jointing is $2J$. Assuming the deterioration due to extra loss is E_v, the iron loss deterioration of core V2 is equal to the sum of these factors, that is, $P+2D+2J+E_v$. In core V3, which is fabricated by applying strain relief annealing to core V2, the strains introduced by punching and dowel formation are eliminated by annealing. Therefore, when the increase in iron loss in core T3 by jointing after annealing is defined as J', the deterioration of V3 is equal to $2J'+E_V$. Here, the extra loss of cores V2 and V3 is considered to be the same, as annealing is presumed to have no effect on the condition of short circuiting between the interlocking points.

P, D, J and E_U, E_V, E_W and E_X were quantified based on the formulae shown in the brackets [ ] in Table 1. For example, J was derived by subtracting the iron loss increment of core T1 ($P+D$) from that of core T2 ($P+D+J$). The ratio of the iron loss increment of each factor obtained in the manner was defined as the ratio γ_{int} with respect to the simple ring core without strain, S3, by the following Eq. (1).

$$r_{int} = \frac{\Delta W}{W(S3)} \times 100\ [\%] \quad \cdots\cdots (1)$$

where,
ΔW: increment of iron loss by each factor originating from interlocking [W/kg]
W (S3): iron loss of core S3 [W/kg]

In Eq. (1), ΔW is equivalent to the iron loss increments P, D and J (defined by core T2) and the extra losses E_U to E_X (defined by cores U to X, respectively). **Figure 9** shows the ratio γ_{int} of the iron loss increment due to each factor for the frequencies used in this study (50 Hz, 400 Hz, 1 kHz). **Figure 10** shows the results when Eq. (1) was applied to hysteresis loss and eddy current loss at 400 Hz, expressed as the ratio to the iron loss of core S3.

In Fig. 9, the increment of iron loss due to interlocking of core T2 corresponds to the sum of D and J. Because $D+J$ is larger than the iron loss increment P due to punching strain at all frequencies, it is clear that the interlocking process has a larger effect than punching strain on degradation of the iron loss of the ring cores fabricated in this research.

As shown in Fig. 9, the ratio of the iron loss increment due to dowel formation (D) decreased as the frequency increased, but no clear correlation with frequency could be seen in the ratio of the iron loss increment due to punching strain (P) or the ratio of the iron loss increment due to jointing (J). When hysteresis loss is the main factor in increased iron loss, the ratio of the iron loss increment generally decreases at higher magnetizing frequencies. Accordingly, the iron loss increment due to dowel formation (D) is mainly due to hysteresis loss. On the other hand, even at higher magnetizing frequencies, there was no large decrease in the

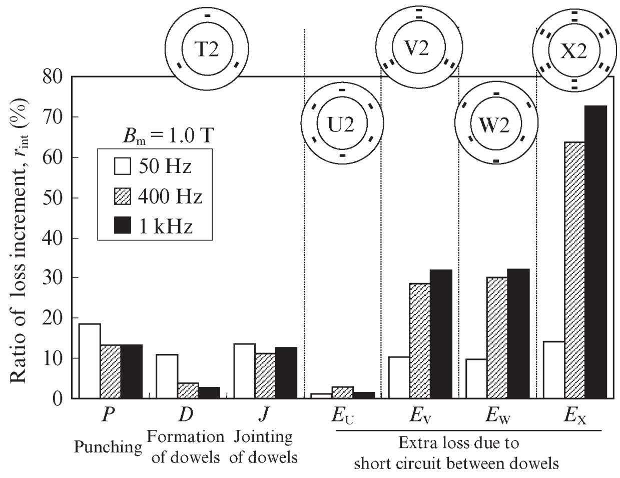

Fig. 9 Ratio of iron loss increment due to each factor related to punching and interlocking

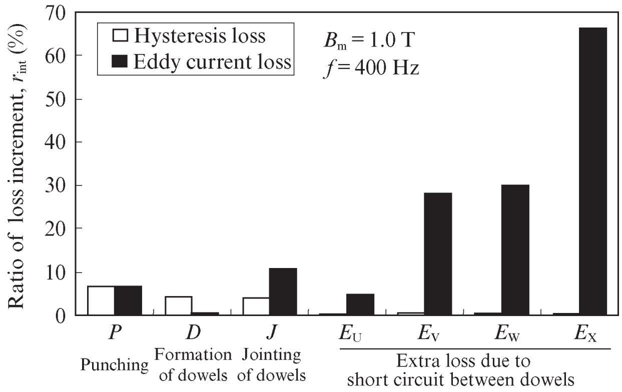

Fig. 10 Ratio of increment in hysteresis loss and eddy current loss due to factors related to punching and interlocking

ratios of the iron loss increment due to punching strain (P) or strain due to dowel jointing (J). Thus, in these factors, the effect was not limited to hysteresis loss, and the effect of eddy current loss was also comparatively large.

In the case of strain caused by dowel jointing (J), short circuit is a conceivable cause of increased eddy current loss, but as shown in Fig. 8 (b), the increment of eddy current loss was small in core T3 and core U3 after strain relief annealing, indicating that short circuits at interlocking point do not have a significant effect on eddy current loss when the interlocking configuration is aligned in a straight line in the direction of the magnetic path, as in these cores. Furthermore, as shown in Fig. 9, in core U2, in which E_U is extremely small and there are 6 interlocks in the center of the magnetic path, virtually no increase in eddy current loss can be seen. This behavior was the same as in core T2. On the other hand, remarkable increases in extra loss occurred in cores V, W and X. Based on the results of separating hysteresis loss and eddy current loss shown in **Fig. 10**, the increase in the extra loss of cores V, W and X is attributable to an increase in eddy current loss. As the reason for the remarkable increases observed in these three cores, in cores with interlinkage flux components across the lines joining two adjacent dowels (in Fig. 2, between a-b, c-d and e-f in core V, and between a-b, c-d, e-f, g-h, i-j and k-l in core X), short circuits between the stacked steel sheets occur at the interlinking points, and this induces an electric current in a short-circuit closed circuit that includes the dowels, resulting in an increase in iron loss. Extra loss similar to that of core V also occurred in core W, which had a staggered dowel arrangement. Because interlinkage with the flux direction occurs in the dowel pairs a-b, b-c, c-d, d-e, e-f and f-a in core W, it is thought that eddy current loss was induced along these paths.

Finally, the results obtained through this research were applied to prediction of the degradation of core loss due to interlocking.

First, the effect of interlinking on hysteresis loss was investigated. **Figure 11** shows the relationship between the number of dowels per 100 mm^2 of one-side ring core area (hereinafter, "dowel density") and hysteresis loss. The hysteresis loss of a core before strain relief annealing and after strain relief annealing has a relationship in which hysteresis loss increases with increasing dowel density, but shows little relationship with the dowel configuration. Therefore, the hysteresis loss of the cores of rotating machinery can be predicted from the relationship in Fig. 11 in cases where the core has the same specifications (interlocking type, dimensions, depth) as in this research.

Next, the effect of interlocking on eddy current loss was analyzed. **Figure 12** shows the effect of dowel density on eddy current loss in cores without dowels (S1, S3) and cores in which extra loss does not occur (T2, T3,U2, U3). In the annealed cores (S3, T3 U3), no increase in eddy current loss can be seen when the dowel density is increased. On the other hand, in the non-annealed cores, eddy current loss increases corresponding to the dowel density. It is estimated that this increase in the eddy current loss of non-annealed cores originates from the local magnetic flux waveform distortion caused by elastic-plastic strain in the core interior, as described previously. If extra loss is not generated by the object rotating machine core, the increase in eddy current loss can be predicted by using the relationship in Fig. 12.

Continuing this discussion, extra loss was analyzed by using the results for the annealed cores. In the following, the two nearest neighbors of interlinking points that have an interlinkage flux are called "interlinking pairs." **Figure 13** shows the relationship between the

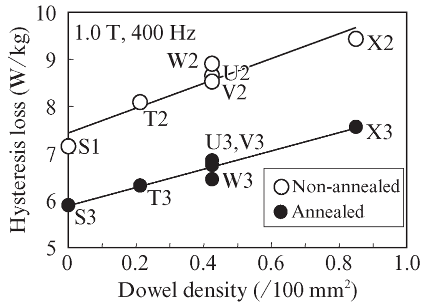

Fig. 11 Effect of dowel density on hysteresis loss

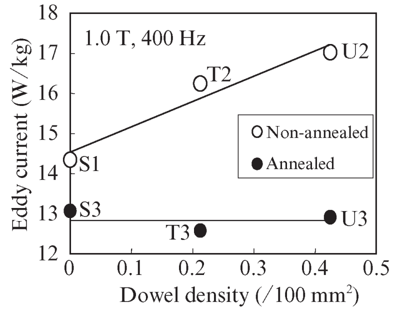

Fig. 12 Effect of dowel density on eddy current loss

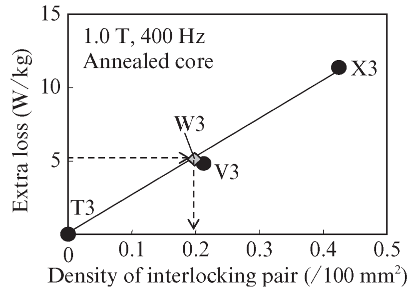

Fig. 13 Effect of density of interlocking pair on extra loss

dowel density (per 100 mm^2 of core area) and extra loss. As shown here, extra loss increases linearly with the density of the interlocking pairs. Furthermore, when the extra loss of core W3 with a staggered core arrangement was applied to the relationship in Fig. 13 and the density of the corresponding interlocking pairs was obtained, the result was 0.2 interlocking pairs/100 mm^2 (equivalent to 3 interlocking pairs in the total core), which is the same as in core V2.

Because the extra loss originating from short circuits at interlocking points also depends on the distance between the interlocking pairs and dowel arrangement, in would not be appropriate to apply the results in Fig. 13 directly to loss analysis of rotating machinery cores with arbitrary interlocking configurations. When interlinkage flux components due to interlocking pairs exists, and it is found that the increase in iron loss exceeds the hysteresis loss and eddy current loss predicted from the relationships in Fig. 11 and Fig. 12, extra loss due to an eddy current flowing in a short-circuit closed circuit caused by interlocking should be suspected.

5. Conclusion

In this research, the factors that cause degradation of magnetic properties were investigated in order to determine the effects of interlocking on the magnetic properties of cores. As a result, it became clear that, depending on the case, the effect of the interlocking process on the core may exceed that of punching, due to the formation of dowels and dowel interlinking. In addition, it was shown that the formation of an eddy current circuit by short circuiting between interlocking points may cause a significant increase in eddy current loss. An experimental method for separating the deterioration factors due to interlocking was also proposed. Based on the relationship between those factors and core characteristics clarified in this study, it is now possible to make approximate predictions of the effects of interlocking on core magnetic properties. We believe that the use of these results as basic data for elastic-plastic analyses of the interlocking process and electromagnetic field analysis of motor cores can contribute to improvement of prediction technologies for core characteristics.

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