Influence of Interlocking on Magnetic Properties of Electrical Steel Laminations

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Interlocking is a suitable method to fix iron cores made of electrical steel sheets along the stack direction. However, this will increase iron loss of the core and, as a result, lower the efficiency and power density of electrical machines. In this paper, the influence of interlocking on the magnetic properties of ring cores is studied and evaluated by measurements. A linear increase of the inverse of magnetic field and iron loss with increasing number of interlocks shows that the influence of interlocking is local. This behavior coincides with the proposed model. Interlaminar eddy currents have no serious impact on the iron-loss properties. Averaged magnetic properties of the magnetically deteriorated regions are calculated according to the magnetic model. These data will be useful for accurate finite-element method calculations of iron losses in electrical machines.

Index Terms—**BH curve, electrical steel sheet, interlocking, iron loss.**

I. INTRODUCTION

ELECTRICAL steel sheets are widely used for magnetic cores in electrical machines such as motors and transformers. To produce motor cores, for example, electrical steel sheets are punched, stacked, vertically fixed by interlocking or welding and finally combined with a frame by shrink fitting. In the vertical fixing process, interlocking is especially suitable for mass production. On the other hand, it is well known that electrical steel sheets are magnetically deteriorated by such manufacturing processes. After these processes, the magnetic permeability decreases and iron loss increases, which lead, e.g., to a lower performance of electrical machines. To take these influences into account, finite-element method (FEM) simulations considering magnetic deterioration are performed. For such FEM simulations, magnetic data for electrical steel sheets considering manufacturing processes are required.

It has been reported that compressive stress [1]–[3], which often appears in motor cores with shrink fitting, and punching [4]–[7] deteriorate the magnetic properties of electrical steel sheets significantly. However, there are only a few reports on magnetic deterioration by interlocking electrical steel sheets [8] and it is required to systematically study the influence of interlocking. In this contribution, measurement results for ring cores with interlocking are presented and the cause of the magnetic deterioration is discussed.

II. EXPERIMENTAL PROCEDURE

Interlocking was applied to ring cores made of electrical steel sheets, because it is difficult to apply interlocking to samples for Epstein frames or single-sheet testers. The structure of the studied ring cores is shown in Fig. 1. The grade of the electrical steel sheets under study is M400-50A. The thickness of the sheets t_1 is 0.5 mm. The outer and inner diameters of the ring cores, d_o and d_i respectively, are 60 and 48 mm. Wire cutting was applied to cut out ring cores from electrical steel sheets to minimize the magnetic deterioration in this process. The overall height of the stack T is about 5, 10, or 20 mm. To prepare ring cores with $T = 5$ mm, for example, ten sheets were stacked. There are 0, 2, 4, or 8 interlocks equally distributed along the circumference of the ring cores. The length and the width of each interlock, a and b respectively, are 4 and 1 mm. Fig. 1(a) shows a ring core with interlocks along the circumferential direction. Ring cores which have interlocks along the radial direction were also prepared. *BH* curves and iron losses at various frequencies were measured.

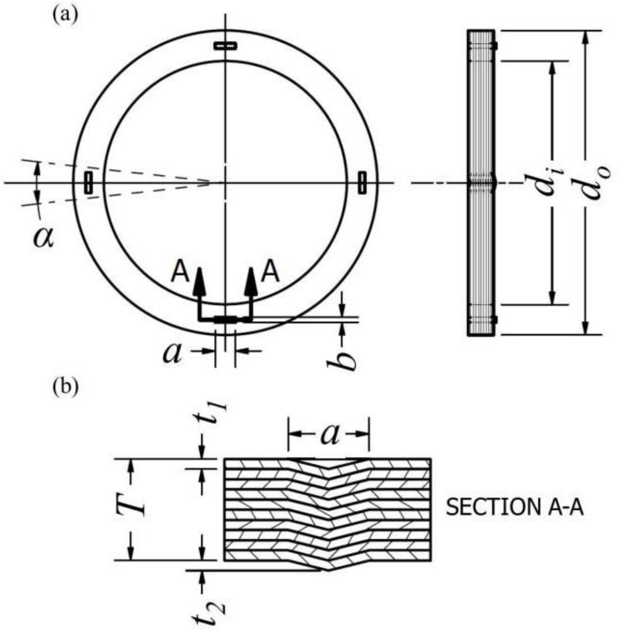

Fig. 1. (a) Plane figure of a ring core with four interlocks along the circumferential direction. (b) Schematic drawing of the cross section of an interlock.

III. MAGNETIC MODEL

We assume that an interlocked ring core is represented by a magnetic series circuit with undamaged and damaged regions.

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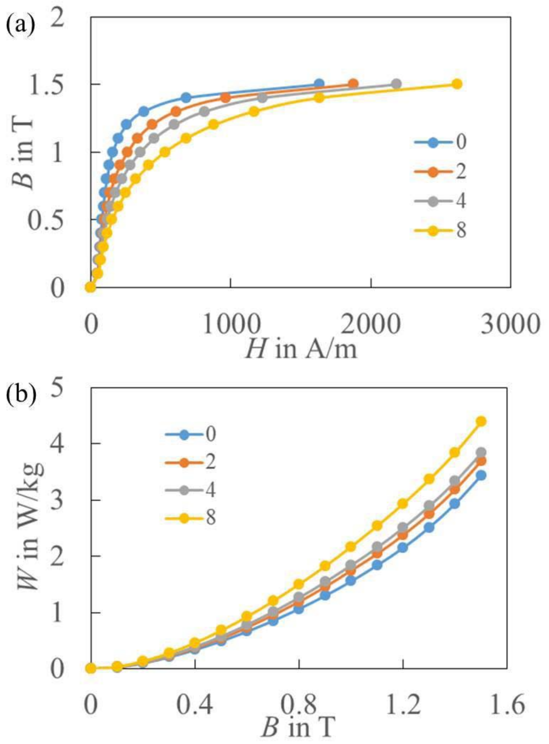

Fig. 2. Measurement results of magnetic properties. 0, 2, 4, and 8 denote the number of interlocks N. The interlocks are along the circumferential direction. (a) BH curves. (b) Iron losses at 50 Hz.

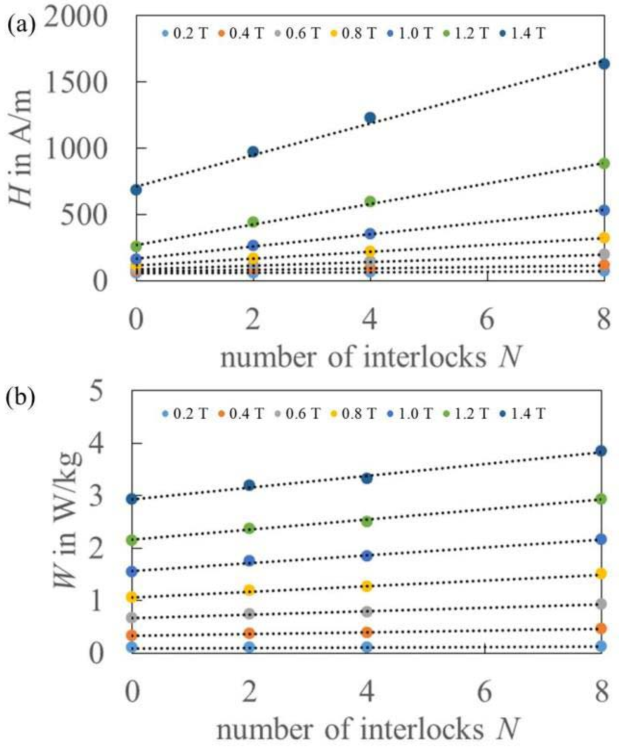

Fig. 3. (a) Magnetic fields obtained by measurements of BH curves. (b) Iron losses at 50 Hz as a function of the number of interlocks. The interlocks are along the circumferential direction. The dashed lines show the linear fitting results.

If there is no leakage of flux from the ring core, the following equations are valid:

$$\frac{l}{\mu_a} = \frac{\mathrm{Nd}}{\mu'} + \frac{(l - \mathrm{Nd})}{\mu} \tag{1}$$

$$W_a = \frac{\mathrm{Nd}}{l} W' + \frac{(l - \mathrm{Nd})}{l} W. \tag{2}$$

Here, μ_a and W_a are the measured permeability and iron loss. μ' and μ are the permeability of damaged and undamaged regions. W' and W are the iron losses of damaged and undamaged regions. N is the number of interlocks in a ring core. l is the average length of the entire magnetic circuit, which is approximated by $l = (d_O + d_i)\pi/2$. d is the length of a damaged region, which is calculated from the angle of this region α by $d = (d_O + d_i)\alpha/4$. Because magnetic damage exists also outside of the interlocks, d should be, for example in samples with interlocks along circumferential direction, larger than a.

These equations show that the inverse of permeability (1) and iron loss (2) should increase linearly with the increasing number of interlocks N.

IV. MEASUREMENT RESULTS

Fig. 2 shows the measurement results of BH curves and iron losses at 50 Hz for $T = 5$ mm. The interlocks are along the circumferential direction. A gradual decrease of magnetic permeability and increase of iron loss with increasing number of interlocks N are clearly observed.

Fig. 3(a) shows the required magnetic fields to reach specific magnetic flux densities as a function of the number of interlocks. The magnetic field, which is proportional to the inverse of permeability when the flux density is fixed, increases linearly with increasing N. The consistency between (1) and the experimental results shows that magnetic deterioration by interlocking is local and that the damaged regions do not interfere with each other at least in the studied sample configurations. Fig. 3(b) shows the N dependence of iron losses at 50 Hz. The iron losses increase linearly with increasing N, which is consistent with (2). It should be noted that these linear behaviors are observed even in high-B regions.

Fig. 4 shows the measurement results for the ring cores with interlocks along the radial direction. The thickness of the sheets and the stack length is the same as is for Fig. 3. It is apparent in Fig. 4(a) that the magnetic permeability of the ring cores with interlocks along the radial direction is lower than those with interlocks along the circumferential direction. This result is reasonable because interlocks along the radial direction disturb the flux distribution more significantly. Similar to the result for the magnetic permeability, the iron losses for the ring cores with interlocks along the radial direction is larger than those with interlocks along the circumferential direction.

Fig. 5 shows the magnetic fields obtained by the measurements of BH curves for $T = 10$ and 20 mm. By comparing Fig. 5 with Fig. 3(a), it is apparent that there is only negligible stack-length dependence of BH curves. This result can be explained by the fact that the magnetic deterioration caused by the internal stress is almost independent of the stack length.

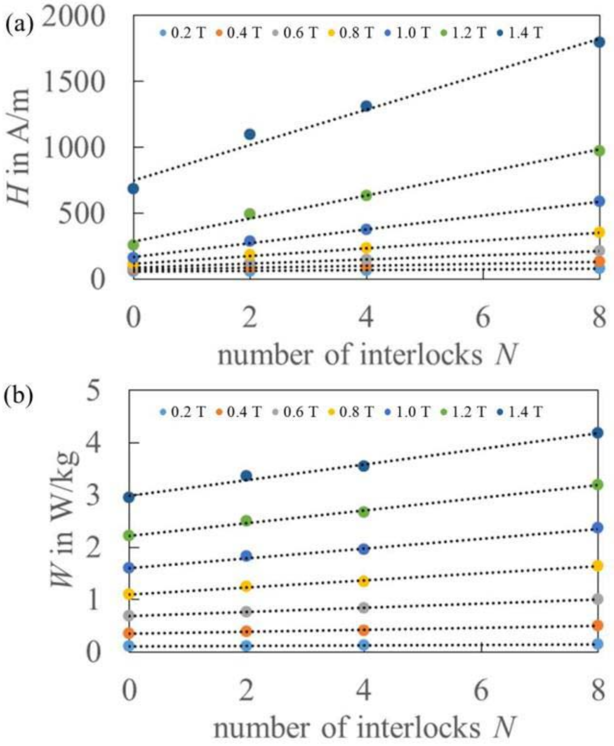

Fig. 4. (a) Magnetic fields obtained by measurements of *BH* curves. (b) Iron losses at 50 Hz as a function of the number of interlocks. The interlocks are along the radial direction. The dashed lines show the linear fitting results.

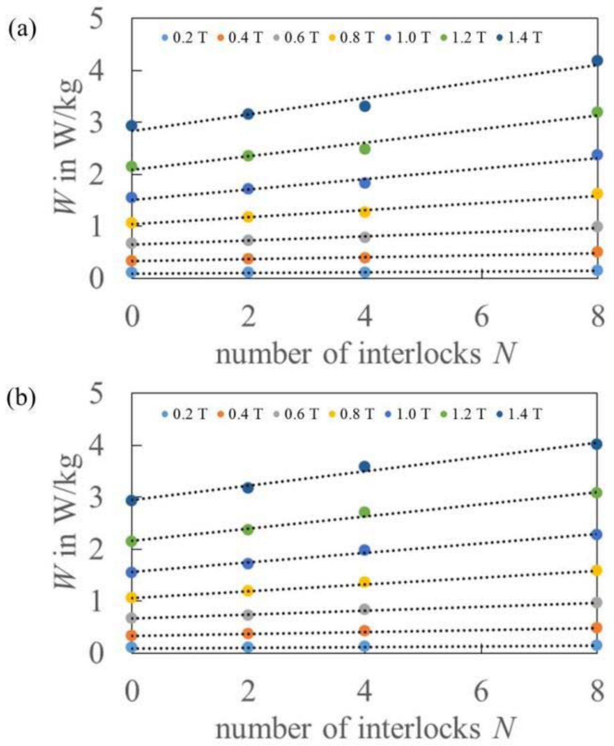

Fig. 6. Iron losses at 50 Hz as a function of the number of interlocks for (a) $T = 10$ mm and (b) $T = 20$ mm. The interlocks are along the circumferential direction. The dashed lines show the linear fitting results.

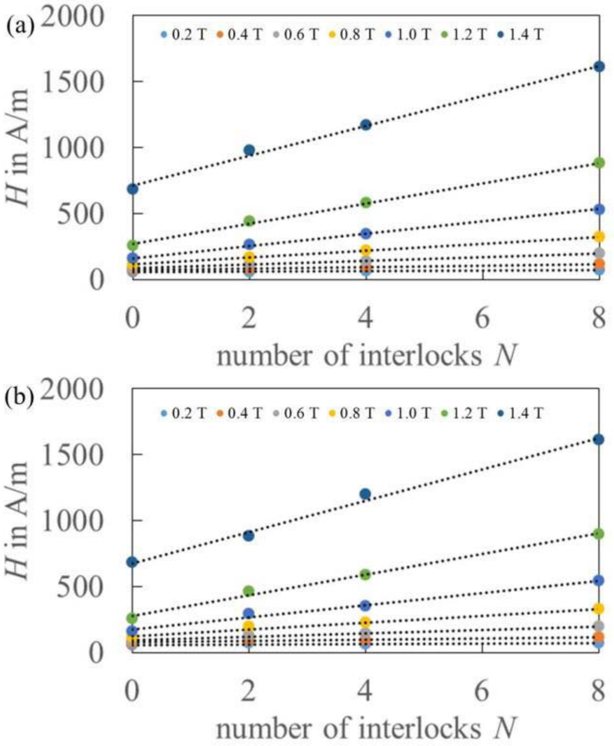

Fig. 5. Magnetic fields obtained by measurements of *BH* curves for (a) $T = 10$ mm and (b) $T = 20$ mm. The interlocks are along the circumferential direction. The dashed lines show the linear fitting results.

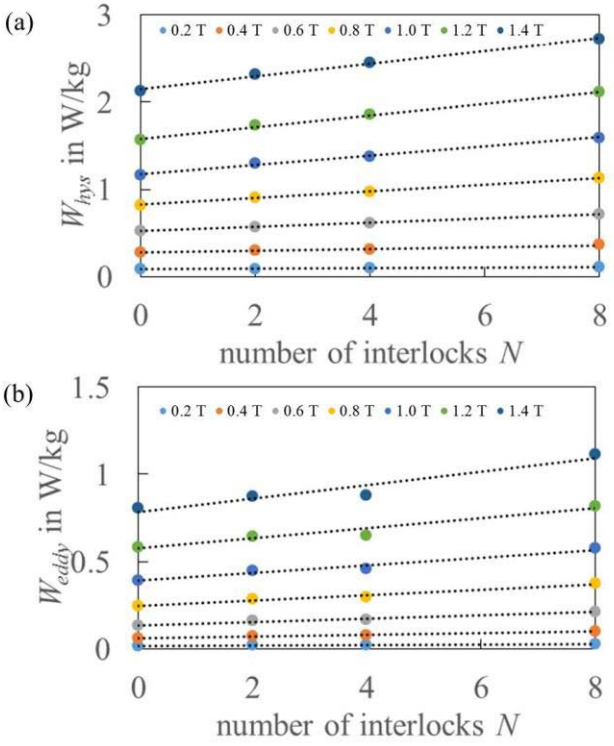

Fig. 7. Hysteresis loss W_{hys} and eddy-current loss W_{eddy} at 50 Hz for $T = 5$ mm. The interlocks are along the circumferential direction. The dashed lines show the linear fitting results.

Fig. 6 shows the iron losses at 50 Hz for the ring cores with $T = 10$ and 20 mm. Only negligible stack-length dependence of the iron losses is observed. This means that the electrical isolation between the sheets is unimpaired even close to the interlocks and that the interlaminar eddy-current loss plays a minor role. However, it should be noted that this result

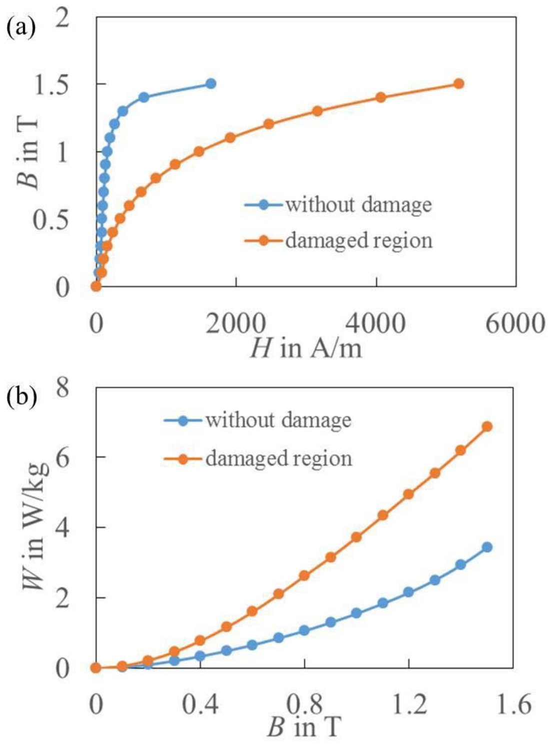

Fig. 8. Calculated results of magnetic properties in the deteriorated region. The result for "without deterioration" is the same as the measurement result without interlocks. The stack length T is 5 mm. The interlocks are along the circumferential direction. The length of the deteriorated region d is assumed to be 6 mm. (a) *BH* curves. (b) Iron losses at 50 Hz.

depends on the coating material of the electrical steel sheets and manufacturing process of the interlocks.

To investigate the particular cause of the increase of iron loss, the iron loss is divided into hysteresis loss W_{hys} and eddy-current loss W_{eddy} according to the following equation and the measurement results for the frequencies f lower than 200 Hz:

$$W = W_{\mathrm{hys}} + W_{\mathrm{eddy}} = K_h f + K_e f^2. \tag{3}$$

Here, K_h and K_e are the coefficients of hysteresis and eddy-current losses. Deviation from (3) by the skin effect is negligible if the frequency is low enough. It should be noted that in the Bertotti's model [9], W_{eddy} is further divided into classical eddy current and excess losses. In this model, above mentioned deviation is attributed to the behavior of excess loss. Fig. 7 shows W_{hys} and W_{eddy} at 50 Hz for $T = 5$ mm. Increase of W_{hys} can be related to internal stress and crystallographic deformation by the interlocking process. The increase of W_{eddy} is attributed to that of the microscopic eddy-current loss, which depends on the magnetic domain structure, because macroscopic in-sheet eddy-current loss is not influenced by interlocking and the interlaminar eddy-current loss is negligible in these samples. In the Bertotti's model, this increment is ascribed to that of the excess loss.

To consider the influence of interlocking on motor characteristics, averaged magnetic properties in the damaged regions are calculated in (1) and (2). Fig. 8 shows the calculation results when it is assumed that d is 6 mm. The stack length T is 5 mm. The interlocks are along the circumferential direction. A drastic decrease of magnetic permeability and increase of iron loss are observed. However, the permeability in the damaged region is still over 100 times larger than that of air. This means that the assumption in our model that there is no flux leakage from the ring core is reasonable. The calculation of electrical machine characteristics with these data would be an interesting future work. Although there should be a gradual change of magnetic properties in the damaged regions, the assumption that the regions are uniformly deteriorated is a good first-order approximation.

V. CONCLUSION

To study the influence of interlocking on magnetic properties of electrical steel sheets, ring cores with interlocking have been measured. It is observed that the inverse of permeability and iron loss increase linearly with the number of interlocks. This result is consistent with the equations of the proposed magnetic circuit model.

Interlocks along radial direction have a more significant impact on magnetic properties than those along circumferential direction. The magnetic properties are almost independent of the stack length. This means that the interlaminar eddy-current loss is negligible. The increase of iron loss by interlocks is attributed to those of hysteresis and microscopic eddy-current losses which are sensitive to internal stress and magnetic domain structure.

Averaged magnetic properties in the deteriorated region are obtained according to (1) and (2). By applying the calculated magnetic properties to FEM simulations, performances of electrical machines will be simulated more accurately.

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