Influence of Interlocking on Magnetic Properties of Electrical Steel Laminations.

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1. 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 an especially suitable method for mass production. On the other hand, it is well known that electrical steel sheets are magnetically deteriorated by such manufacturing processes. After the processes, permeability decreases and iron loss increases, which lead e.g. to a lower performance of motors. To take these influences into account, finite element method (FEM) analyses considering magnetic deterioration are performed. For such FEM analyses, magnetic data for electrical steel sheets considering such 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 electrical steel sheets significantly. However, there are few reports on magnetic deterioration by interlocking electrical steel sheets 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. 2. Experimental procedure Interlocking was applied to ring cores made of electrical steel sheets. This is 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 (a). The material used is non-oriented electrical steel containing about 3 wt% of silicon and some other elements to improve soft magnetic properties. 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 mm and 48 mm. The overall height of the stack T is 5 mm. 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 mm and 1 mm. Fig. 1 (b) shows the schematic drawing of the cross section of an interlock. *BH* curves and iron losses at the frequency of 50 Hz were measured. 3. Magnetic model We assume here that an interlocked ring core is represented by a magnetic series circuit with undamaged and damaged regions. If there is no leakage of flux from the ring core, the following equations are valid. $l/\mu_a=Nd/\mu_+ +(l-Nd)/\mu_-$ (1) $W_a=NdW_+/l+(l-Nd)W_-/l$ (2) Here, μ_a and W_a show the measured permeability and iron loss. μ_+ and μ_- show the permeability of damaged and undamaged regions. W_+ and W_- show 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 approximated by $\pi(d_o + d_i)/2$. d is the length of a damaged region. These equations show that the inverse of permeability and iron loss should increase linearly with the increase of N. 4. Measurement results and discussion Fig. 2 (a) shows the magnetic fields obtained by measurements of *BH* curves. Magnetic field, which is proportional to the inverse of permeability when the flux density is fixed, increases linearly with the increase of N. The consistency between Eq. (1) and the experimental results shows that magnetic deterioration by interlocking is localized and the damaged regions do not interfere with each other at least in these sample configurations. Fig. 2 (b) shows N dependence of iron losses at 50 Hz. Iron loss increases linearly with the increase of N, which is consistent with Eq. (2). It should be also noted that these linear behaviors are observed even in high-B regions. By solving Eq. (1) and (2) for each flux density, an averaged *BH* curve and iron losses in the damaged region are obtained. 5. Conclusions To study the influence of interlocking on magnetic properties of electrical steel laminations, ring cores with interlocking have been measured. The inverse of permeability and iron loss increases linearly with the number of interlocks. This result is consistent with the equations of the magnetic circuit. Averaged magnetic properties in the damaged region are obtained according to Eq. (1) and Eq. (2). By applying the calculated magnetic properties to FEM analyses, performances of electrical machines will be simulated more accurately. In the full paper, the influence of frequency, orientation of interlocks, stacking length, and thickness of the sheets will be also shown and discussed. This allows one to separate iron losses into static and dynamic losses due to the magneto-mechanical effect and interlaminar short circuits.

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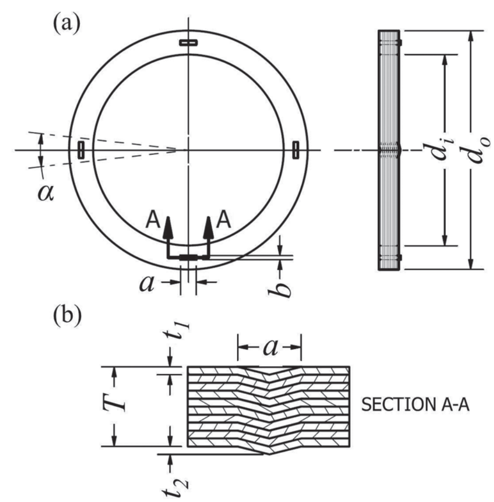

Fig. 1. (a) A technical drawing of the studied ring core geometry with four interlocks, and (b) a schematic view of the cross section of an interlock. The length of a damaged region d is calculated from the angle of that α by $d = (d_o + d_i)\alpha/4$.

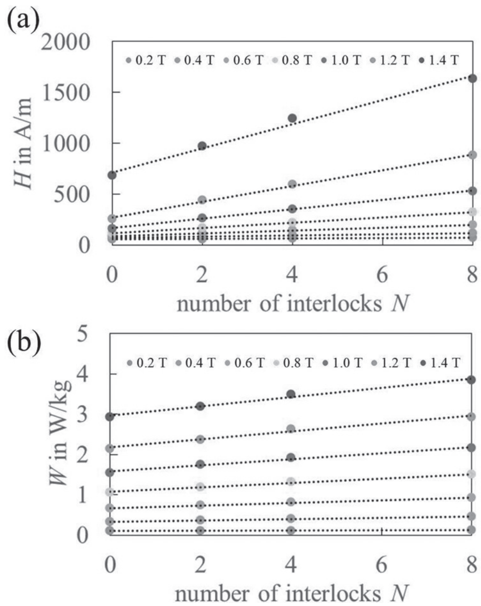

Fig. 2. (a) Magnetic fields obtained by measurements of *BH* curves, and (b) iron losses at 50 Hz as a function of the number of interlocks.