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Interlocking Performances on Non-Oriented Electrical Steels

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Interlocking performance as fastened strength and magnetic deterioration by interlocking were investigated. The thickness of a surface insulation coating affected the interlocking fastened strength. Sheets with a thin coating resulted in a better interlocking performance than those with a thick coating due to the lubricating effect by resin as coating materials. Sheet gauge affected the interlocking fastened strength. The fastened strength of thin gauge sheet was less than that of a thick one, because of the reduction of the sticking area of interlocking protuberances. The protuberance shapes affected the fastening strength. The rectangular types are stronger than the circular ones, due to the 'hooked by corners' effect. Magnetic deteriorations by interlocking was caused by the core loss increased by the obstruction of magnetic flux flows and eddy current loss through the laminations. The core loss increased by the eddy current loss through the laminations was 78% of all deterioration by interlocking.

Keywords core loss, fastening strength, interlocking, protuberance, surface insulation coating

1. Introduction

Core manufacturing is the key process in motor or ballast industries. Electrical steel sheets are stamped and stacked manually or automatically in the die system, which is called interlocking. Although manual stacking such as fastening by bolt or welding was low productivity, interlocking in the die system is widely used in small motor or ballast core makers. Interlocking is a simple process: first make a protuberance on the surface; then ram the protuberance down into the next lamination from the backside hole. Perpendicular to the surface direction of the stacked core, the fastened strength is very important for the core making process. Weak or imperfect fastening causes many troubles during the coil winding.

Nakayama et al. (Ref 1), Nakayama and Honjou (Ref 2), and Nakayama (Ref 3) reported the interlocking performance on non-oriented electrical steel sheet and concluded that the thickness of the insulation coating on the surface strongly affected the interlocked strength. Beckley (Ref 4) showed the cross-section of the interlocking and explained how it worked.

Fujimura et al. (Ref 5) studied the effect of stress of interlocking on the magnetic properties and concluded that the stress from interlocking deteriorated the magnetic properties dramatically. The annealing after interlocking the core relieved the stress and recovered some of the magnetic properties. In this article, we studied the interlocking performances on the non-oriented electrical steel sheet both mechanically and magnetically.

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2. Experimental Procedures

2.1 Materials

The details of the electrical steel sheet used in these investigations are given in Table 1.

All sheets were coated with surface insulation (X1 coating) made of resin and inorganic materials designated CS-2 in JIS C 2550 (2000). The nominal thickness of the X1 coating was 0.4 μm. A thin coating was about 0.3 μm and the thick was 0.6 μm.

2.2 High-Speed Stamping and Interlocking

Stamping and interlocking were performed by a 25 ton high-speed crank-press machine (Yamada-Dobby) with the FASTEC interlocking die system (Kuroda precision) at 200–250 spm (strokes per minute). The dimensions of the ring core in this study are illustrated in Fig. 1, and the dimensions of the four interlocking protuberance types (FC, VC, FR, and VR) are shown in Fig. 2. Die clearance was set at 5–8% of the stamping sheet thickness and kerosene-based stamping lubrication oil (Daphne New Punch Oil made by Idemitu Kosan Co., Ltd.) was used.

2.3 Fastening Strength Measurements

The fastening strength of the four points interlocked in the lamination core was measured by the Amslar universal testing machine (Shimadzu Corp.: maximum range 20 kN), using J-shaped hooks through the lamination direction.

2.4 Magnetic Measurements of Interlocked Core

Magnetic measurements were done at 50 Hz and 1.0 T (W10/50) in the condition of the primary coil winding for magnetizing as 100 turn and secondary winding for detecting as 100 turn on the ring core shown in Fig. 1.

3. Results and Discussion

3.1 Effects of Insulation Coating

Electrical steel sheets are usually coated with organic, inorganic, or an organic and inorganic mixture of insulation on the surface. Stamping performance or die worn rate of the electrical steels with organic material as the surface insulation is better than that without organic insulations. Japanese Industrial Standard (JIS) C-2552 classified the surface insulation to CS-1 (inorganic) and CS-2 (organic and inorganic mixture), and designated CS-2 as performing better in high-speed continuous stamping. This means that the organic insulation plays a lubrication role between steel and die at stamping. Figure 3 shows a relationship between the insulation coating thickness and burr height as a result of die wear in continuous stamping.

As the coating thickness was increased, stamping performance was improved due to the lubrication performance by the thick organic layer.

However, this lubrication caused the interlocking performance to reduce the fastened strength. Figure 4 shows the relationship between coating thickness and fastened strength. As the coating thickness was increased, the fastened strength was decreased. In order to check the lubricating role, we investigated the cross-section of a sheared surface. Figure 5 shows the Cr distribution map on the cross-section of the

Table 1 Electrical steels

		Core loss[b], W/kg			Magnetic induction[b], T		
Designation[a]	Thickness, mm	W10/50	W15/50	W10/400	B3	B25	B50
20SX1500	0.20	1.02	2.39	12.9	1.31	1.55	1.64
27SXH270	0.27	1.09	2.44	16.6	1.38	1.64	1.73
35SX270	0.35	1.07	2.45	18.3	1.31	1.59	1.68
50SX400	0.50	1.49	3.28	30.3	1.34	1.62	1.71
50SX1300	0.50	3.93	8.06	68.5	1.30	1.67	1.76

[a]All steels used in this study were commercial grades manufactured by Sumitomo Metal Industries, Ltd
[b]All data in this table were measured in accordance with JIS C 2550 (Ref 6). Half of the test pieces were sampled in the rolling direction and the rest in the transverse direction

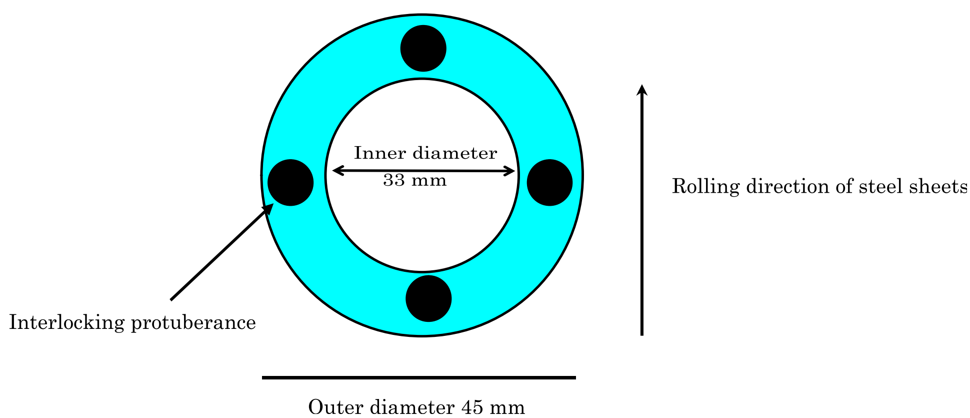

Fig. 1 Dimensions of ring core

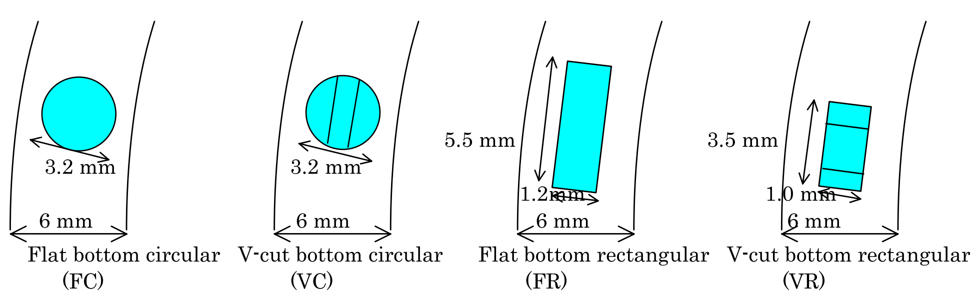

Fig. 2 Dimensions of interlocking protuberances

interlocking, by electron probe micro-analysis (EPMA). By the observation of the sheared area in the cross-section, the scattered coating fragments on the thick-coated (~0.6 μm thick) sheet are more than that on the thin-coated (~0.3 μm thick). These coating fragments play a lubricating role and affect the fastened strength.

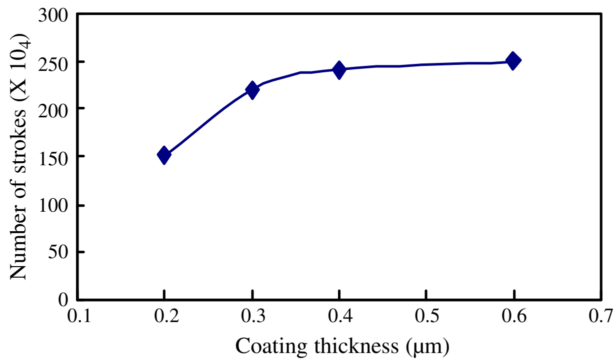

Fig. 3 Effect of surface insulation coating thickness on the stamping performance (50SX1300)

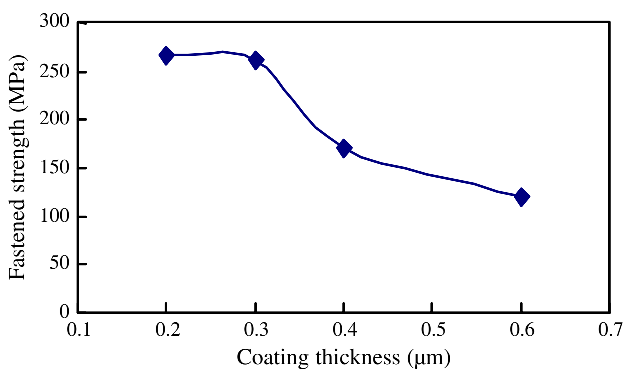

Fig. 4 Effect of surface insulation coating thickness on the interlocking fastened strength (50SX1300)

3.2 Effect of Sheet Gauge and Protuberance Shapes

Although interlocking is a fastening by the friction at the cross-section, thin gauge sheets have disadvantages with stacking strength. Figure 6 shows the relationship between sheet gauge and stacking strength. Thin gauge sheet (i.e., 0.2 mm thick) was o weakly fastened that it needed careful handling during core making or coil winding. For easy use and handling, 0.27 mm thick sheet is the thinnest gauge on the usual high-speed stamping for building a small-size motor. Kabasawa and Takahashi (Ref 7) reported that they applied the 0.27 mm thick non-oriented electrical steel sheet for hybrid electrical vehicles and mentioned that the 0.27 mm thickness sheet has the optimal balance between stacking strength and low core loss at high frequency.

Figure 7 shows the effect of protuberance shape and fastened strength. We used four types of protuberances, two rectangular ones and two circular ones. The results of this test indicated that the rectangular type protuberances are fastened more strongly than circular types. This is an effect of ‘hooked by corners’ on the rectangular protuberances.

3.3 Magnetic Deterioration by Interlocking

The deterioration of magnetic properties was caused by not only a simple obstacle of magnetic flux flow, but by flow from lamination to lamination through the interlocking protuberances and by compression or expansion stress between two fastened protuberances.

Fastening by rectangular flat-bottom-type interlocking (FR in Fig. 2) makes it easy to calculate the magnetic deterioration. In this core, the occupied volume by the protuberances is 3.6% of the total core volume. To apply the real motor or ballast cores, these percentages are high in the home appliance motor cores, but very close to the micro-motor cores such as a spindle motor in hard disk drives or fan motors in the personal computers.

To separate the core loss increase by increasing magnetic induction in the narrowed protuberance area and the increase by the magnetic flow through laminations from the total core loss, we adopt very simple calculation. Fujimura et al. (Ref 5)

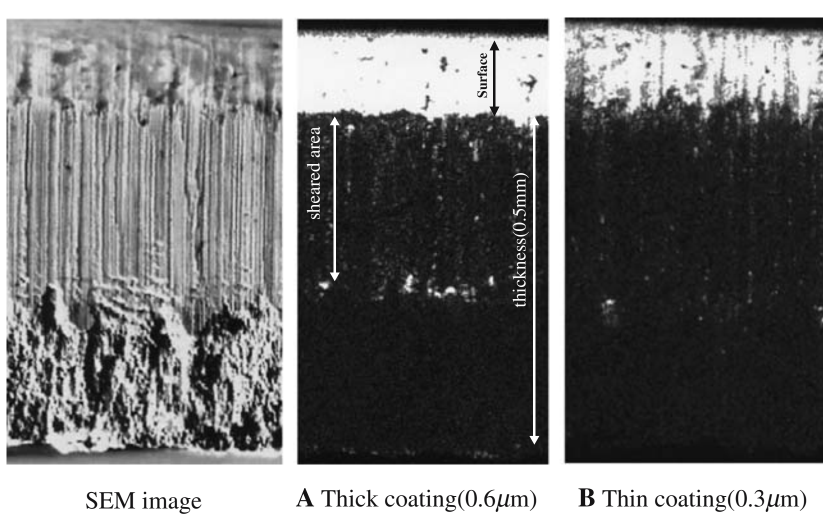

Fig. 5 Cr distribution on the cross-section of interlocking protuberances by electron probe micro-analyzer (EPMA; bright: high intensity → dark: low intensity)

reported the stressed area after stamping in the electrical steel as within a 0.5 mm region from the cut-edge by measuring the hardness change. Therefore, we assume no magnetic flux flows in the protuberances and near the region within 0.5 mm from the cut-edge as deteriorated by stress, as shown in Fig. 8.

Magnetic flux was concentrated in the narrowed cross-sectional area beside protuberances. As magnetic flux density increased, the core loss increased at the narrowed point. When using the core with the rectangular protuberances and magnetizing at 1.0 T, magnetic flux density was calculated to be about 1.43 T within the narrowed area near the protuberances. That in the rest of the ring was calculated to be 0.91 T, based on 18% of the total ring area. The magnetic properties were deteriorated by the protuberances. From the magnetic induction and iron loss curve (Fig. 9), these core losses were estimated as 3.80 W/kg at the affected area and as 1.62 W/kg at nonaffected areas. Thus the total core loss was calculated as 2.01 W/kg, 82% of 1.62 W/kg and 18% of 3.80 W/kg, only by the narrowing effect. This means that the subtraction of the measured core loss without the protuberance (1.93 W/kg) from this calculated core loss (2.01 W/kg), 0.08 W/kg, was estimated as the deterioration by the protuberance obstacles. However, the measured core loss with the protuberances was 2.29 W/kg; therefore the subtraction calculated core loss (2.01 W/kg) from the measured (2.29 W/kg), 0.28 W/kg, was estimated as the core loss increase through the laminations at the protuberances shown in Fig. 10.

To estimate more precise core loss deterioration, we need more precise framework models such as finite element method, and we need an easy estimation of the deterioration by interlocking. The calculation results indicated that only the 3.6 vol% protuberances occurred the 18% core loss increase, and 78% of this increase was estimated mainly by the eddy current loss through the lamination. This means that the interlocking

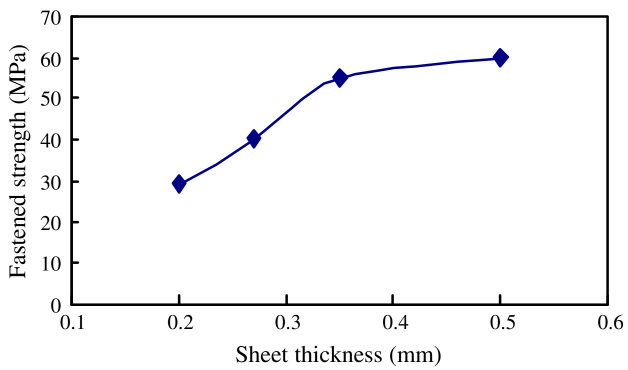

Fig. 6 Gauge effect on interlocking fastened strength (protuberance: VC)

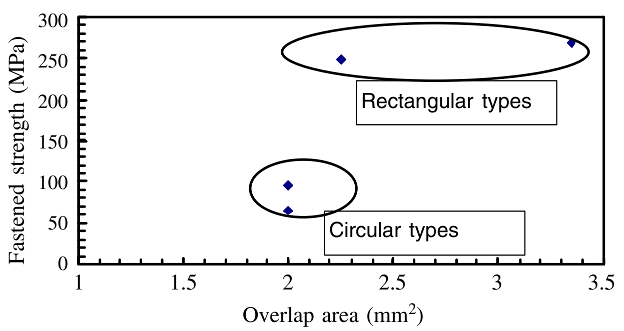

Fig. 7 Effect of the protuberance shape on the fastened strength (50SX400)

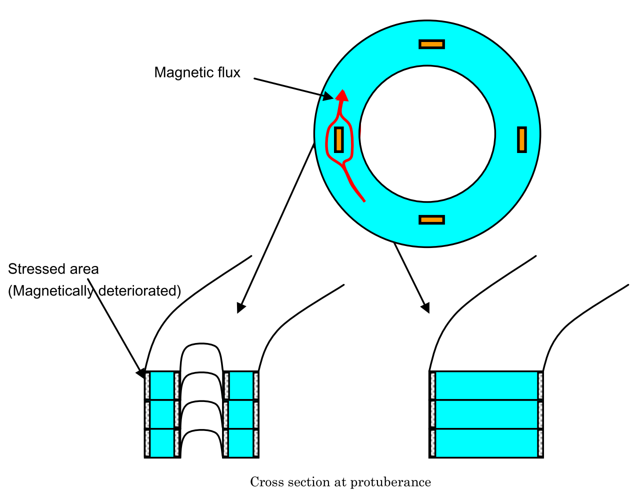

Fig. 8 Magnetic flux model in ring core

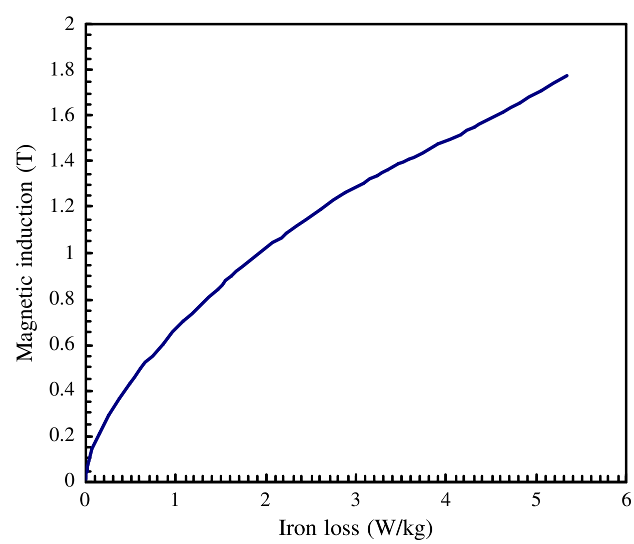

Fig. 9 Iron loss curve on the magnetization (50SX400)

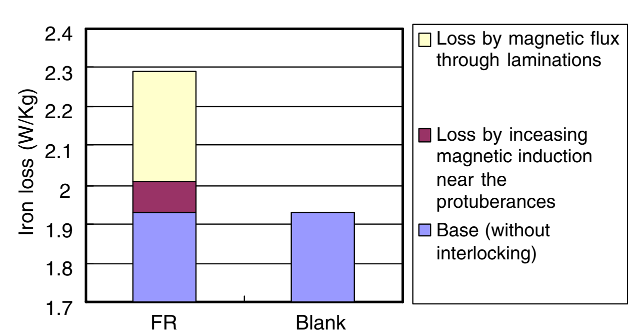

Fig. 10 Deterioration analysis on the interlocked core (FR)

protuberances seriously affect the magnetic circuit on the small motor cores.

4. Conclusions

In this study, we concluded the interlocking properties as the following:

1. Surface insulation coating thickness affects the interlocking fastened strength. Sheets with a thin coating gave a better result for interlocking performance than those with a thick one due to the lubricating effect of the resin in the coating.
2. Sheet gauge affects the interlocking fastened strength. Thin gauge sheet has a lower fastened strength than a thick one, due to the reduction of the sticking area of the interlocking protuberances.
3. Core loss deteriorations by interlocking is estimated mainly by the eddy current passing through the lamination. The core loss increase by increasing the magnetic induction caused by the narrowing area near the protuberances is less affected on the total magnetic deterioration.

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