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Evaluation of the Magnetic Properties of the Rotating Machines for the Building Factor Clarification

***Abstract**. In order to know how much iron loss of an actual stator core increase in each manufacturing process, we are developing the magnetic property evaluation method of a rotating machine. In this research, we prepared two kinds of specimens, including piled up five punched electrical steel sheets that are the shape of the actual stator core and laminated punched electrical steel sheet in the shape of the actual stator core. The specimen of piled up five punched electrical steel sheets is called a punched specimen and the laminated punched electrical steel sheet is called the laminated specimen. The magnetic properties were measured using the excitation coil and the search coil that was wound in the back yoke of the two specimens. This method is called the direct winding method. The evaluated magnetic properties were the iron loss, the coercive force, the residual magnetic flux density, and the maximum excitation magnetic field strength. The experimental results showed that these measured magnetic properties clearly depended on the manufacturing process, such as the laminating process. The iron loss was increased by the laminating process by about 4.7% when the maximum excitation magnetic flux density (B_{ex}) is 1.35 T. In this paper, the influence that the laminating process exerts on magnetic properties of an actual stator core is reported in detail.*

***Streszczenie.** Zbadano jak zmieniają się straty magnetyczne rdzenia stojana w wyniku procesu produkcji. W tym celu zbadano próbki w kształcie blach stojana. Badano straty, koercję, indukcję i natężenie pola magnetycznego. Stwierdzono, że parametry te bardzo zależą od procesu produkcji rdzenia. W wyniku laminowania straty wzrosły o 4.7% przy indukcji 1.35 T. (**Ocena zmiany parametrów magnetycznych blach maszyn elektrycznych w wyniku produkcji rdzenia**)*

Keywords: rotating machine, stator core, iron loss, coercive force, residual magnetic flux density, silicon steel sheet.
Słowa kluczowe: maszyny elektyryczne, straty, rdzeń stojana.

Introduction

Recently, the necessity of saving energy has often been discussed in terms of the global warming issue. This issue originates in an increase of carbon dioxide by the heavy consumption of the fossil fuels used to generate electrical power. Big energy is being consumed by the rotating machines that are used in the home and industry field today. In Japan, according to statistical data, it is reported that half of the electrical power consumed was by rotating machines. Therefore, it is especially important in the conservation of energy such as electrical power to make highly effective rotating machines of low power consumption.

In the design of the rotating machine, the iron loss after the rotating machine is completed is larger than the iron loss of an unprocessed electrical steel sheet that is written in the catalogue. It is believed that the manufacturing process of the rotating machine is the cause of an increase in the iron loss. This problem is referred to as the building factor problem. The building factor, a value in which the ideal iron loss of a rotating machine that was unprocessed is divided by the actual iron loss of the completed rotating machine, often exceeds one. This indicates that the increase of the iron loss occurs at each manufacturing process of a stator core used in the rotating machine. The machine work of the electrical steel sheet causes the distortion and the residual stress, etc. in the electrical steel sheet. The distortion and the residual stress of the electrical steel sheet used in a stator core are the causes of the iron loss increase, which also generates the degradation of the magnetic properties of a stator core made from punched electrical steel sheets. However, a method of knowing the amount of the iron loss that increases by each manufacturing process has not yet been established [1, 2, 3, 4].

In order to determine the iron loss as it increases during each manufacturing process, we designed the iron loss evaluation method using the excitation inner core [5, 6]. This method can be used to relatively measure the change in the iron loss and the other magnetic properties of the actual stator core during several manufacturing processes. Then, we evaluated the iron loss of the stator core after the laminating process and again after the shrink-fitting process [7, 8]. The iron loss of the stator core increases by about 10 % after these manufacturing processes. Moreover, the other magnetic properties (coercive force (H_c), the residual magnetic flux density (B_r), and the maximum excitation magnetic field strength (H_{max})) of the stator core similarly changed, and the degradation of the magnetic properties of the stator core by the processing was shown.

In our conventional paper, the degradation of the magnetic properties by the laminating process of the stator core is not reported. Then, we compared the magnetic properties of the back yoke of the punched specimen and the magnetic properties of the back yoke of the laminated stator core. In this paper, the change in the magnetic properties of an actual stator core after the laminating process was investigated. As a result of the experiment, the magnetic properties were deteriorated because of the laminating process by several percent.

Evaluation method of the iron loss

It is established that the iron loss (W_i) of an electrical steel sheet used in a rotating machine can be evaluated using equation (1).

$$W_i = \frac{1}{\rho T}\int_T H \cdot \frac{dB}{dt}\,dt \tag{1}$$

In this equation, H and B are the magnetic field strength and the magnetic flux density of a stator core respectively. In addition, ρ is the density of an electrical steel sheet and T is the period of the excitation current. In order to evaluate the iron loss, it is necessary to measure H and B in the back yoke of the punched specimen and of the laminated specimen as accurately as possible. Additionally, H and B can be evaluated using equations (2) and (3).

$$H = \frac{N_e I}{L_e} \tag{2}$$

$$B = \frac{1}{N_s S}\int v\,dt \tag{3}$$

In these equations, I, N_e, L_e, N_s, and S are the excitation current, the number of turns of the excitation coil, the effective magnetic path length, the number of turns of the search coil, the sectional area of the punched specimen, and the laminated specimen respectively. H is obtained from I, N_e, L_e, and measured I. In addition, B is obtained by using v, which is an induced voltage of the search coil wound on the back yoke.

Specimens

In this research, we prepared electrical steel sheets punched onto the shape of the stator core. Then, we prepared two kinds of specimens such as the punched specimen and the laminated specimen as shown in Fig. 1 (a) and (b). Parts of the laminated specimen are composed of the punched specimen. The laminated specimen is an actual stator core for the small size three-phase induction motor with 36 teeth. The internal diameter of the laminated specimen is 95 mm, the outside diameter is 157 mm, and height is 65 mm.

The excitation coil and the search coil were wound on the back yoke as shown in Fig. 2. The number of turns of the excitation coil is 72. The winding used a Holmal wire that was 0.8 mm in diameter. The search coil for the magnetic flux density measurement rolled the Holmal wire (0.2 mm in diameter) three times.

Because the excitation coil has been wound as shown in Fig. 2, it is thought that most excitation magnetic flux passes in the back yoke of the specimen. Then, the value of B in the punched specimen and the laminated specimen can be measured accurately using the search coil method. In order to evaluate B by measurement, search coils are wound on the back yoke of the punched specimen and of the laminated specimen. The value of H in them can be easily evaluated because their shape is simple as shown in Fig. 2. Then, the value of H was calculated by the assumed effective magnetic path length (L_e) that was assumed to be the length of the circumference of which the radius was the value of the average of the internal and the outside radius of the specimen. Magnetic properties were calculated using this assumed L_e.

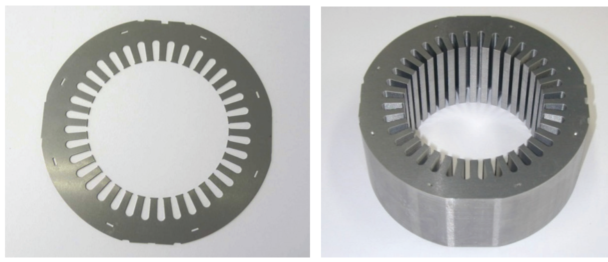
Measurement system

The block diagram of the measurement system to evaluate magnetic properties is shown in Fig. 3. The resolution of the A/D converter and the D/A converter used in this experiment is 14 bits and 16 bits respectively. Moreover, the highest sampling frequency of the A/D converter is 100 kHz. The excitation voltage outputted from the D/A converter amplified with the power amplifier is applied to the excitation coil on the back yoke of the specimen. The waveform of the excitation voltage is controlled by feedback so that the maximum excitation magnetic flux density (B_{ex}) in the back yoke of the specimen becomes a sinusoidal wave. The excitation current is measured from the voltage generated in the shunt resistor (0.1 Ω). The generated voltage in the shunt resistance is input into the computer with the A/D converter. Similarly, to measure the magnetic flux density in the specimen, the induced voltage of the search coil is input into the computer with the A/D converter. The iron loss is calculated by using the output voltage of the search coil, the magnetic field strength calculated by using the assumed L_e, and the measured excitation current. The change in the iron loss of the stator core according to B_{ex} is expected. Then, the value of B_{ex} was applied from 0.4 T to 1.35 T by 0.05 T steps. The excitation frequency used in this experiment is 50 Hz. The magnetic properties were measured three times, and the three measurement values were averaged.

Results and Discussions

B-H curves of the punched specimen at each B_{ex} are shown in Fig. 4. Figure 5 shows the *B-H* curves of the laminated specimen at each B_{ex}. In these two figures, B_{ex} was from 0.4T to 1.35 T. However, in the case of the same maximum magnetic flux density in a *B-H* curve is compared in both figures, H_{max} of the laminated specimen is growing more than H_{max} of the punched specimen. Then, the slope of *B-H* curves of the laminated specimen is smaller than the slope of *B-H* curves of the punched specimen.

In order to clarify the change of the *B-H* curve by the influence of the laminating process, Figure 6 shows *B-H* curves of the punched specimen and the laminated specimen when B_{ex} is 1 T. The solid line is the *B-H* curve of the punched specimen, and the short dashed line is that of the laminated specimen. H_c of the *B-H* curve of the laminated specimen is more than that of the punched specimen. On the other hand, B_r of the laminated specimen is smaller than that of the punched specimen. From this figure, it can be said that the magnetic properties of the laminated specimen are obviously more deteriorated than those of the punched specimen. Therefore, it can be said that the core loss increases as well.



(a) The punched specimen (b) The laminated specimen

Fig. 1. The punched specimen and the laminated specimen.

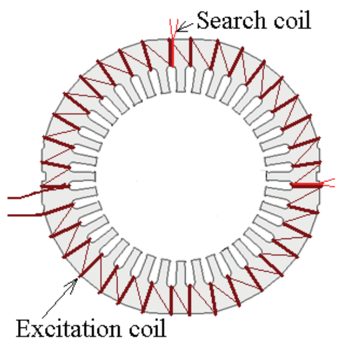


Fig. 2. Arrangement of the excitation coil and the search coil in the direct winding method.

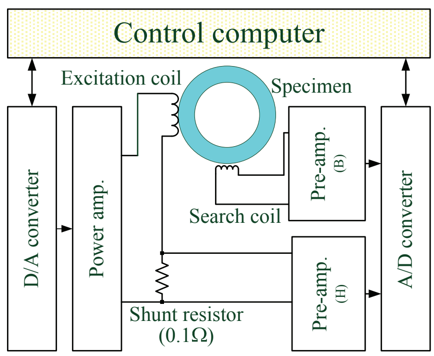


Fig.3. The block diagram of measurement system.

Figure 7 shows the relationship between iron losses (W_i) of the punched specimen and the laminated specimen and B_{ex}. It is understood that the iron loss increases by the laminating process although there is no big difference in the iron loss of either. The iron loss was increased by the laminating process by about 4.7 % when B_{ex} is 1.35 T.

The relationship between coercive force (H_c) of the punched specimen and the laminated specimen and B_{ex} is shown in Fig. 8. In this case, the value of H_c doesn't depend on B_{ex} and increases by about 10 A/m by the laminating process. The increase rate of H_c is about 3.2 %.

Figure 9 shows the relationship between B_r of the punched specimen and the laminated specimen and B_{ex}. From this figure, B_r decreases by the laminating process. The decrease rate of B_r is about 5.5 % when B_{ex} is 1.35 T.

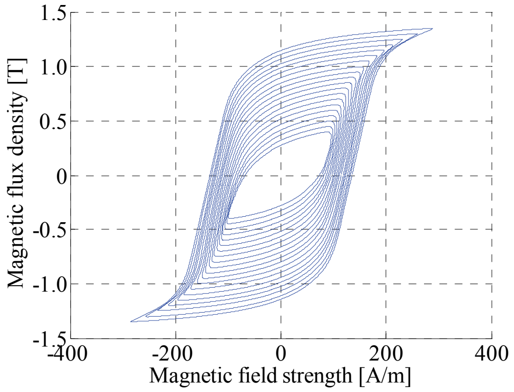


Fig.4. *B-H* curves of the punched specimen.

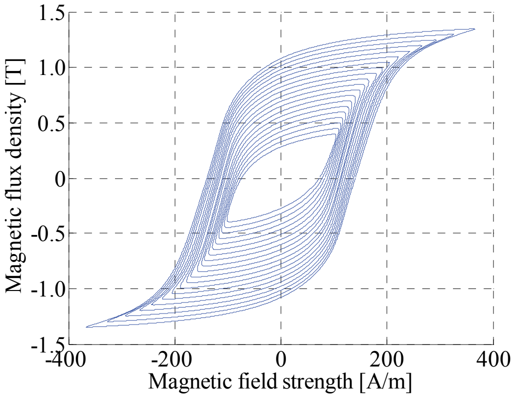


Fig.5. *B-H* curves of the laminated specimen.

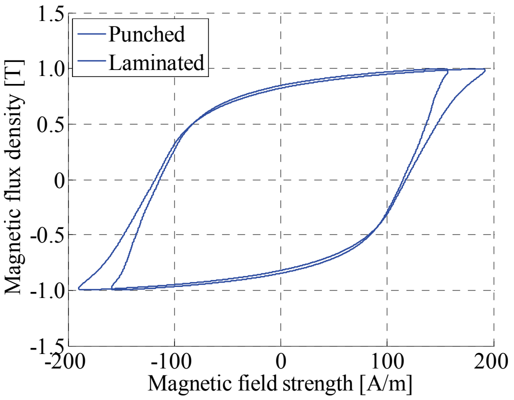


Fig.6. *B-H* curves of the punched specimen and the laminated specimen (B_{ex}=1T).

Figure 10 shows the relationship between H_{max} of the punched specimen and the laminated specimen and B_{ex}. This increases by about 90 A/m by the laminating process when B_{ex} is 1.35 T. The increase rate of H_{max} is about 26 % when B_{ex} is 1.35 T. H_{max} receives the biggest influence in the measured magnetic properties in this experiment by the laminating process.

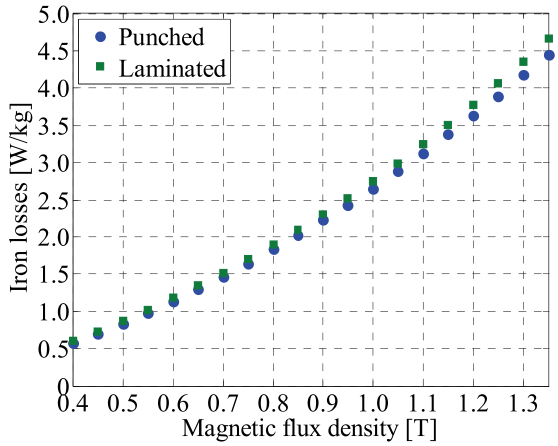


Fig.7. Iron loss (W_i) of the punched specimen and the laminated specimen.

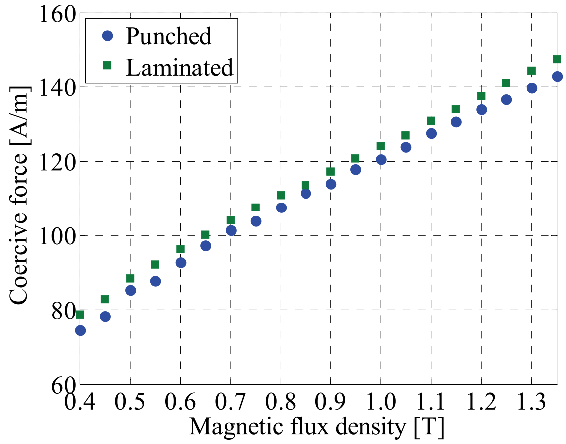


Fig.8. Coercive force *(H_c)* of the punched specimen and the laminated specimen.

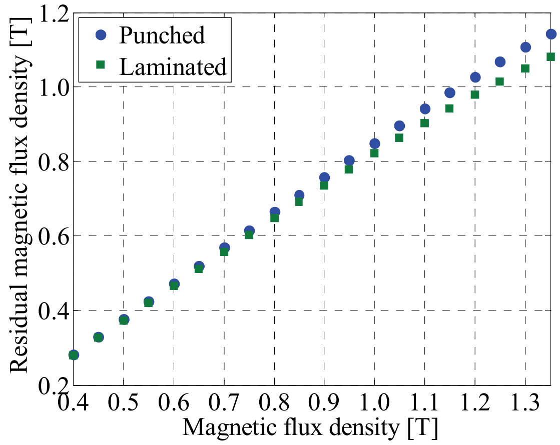


Fig.9. The residual magnetic flux density (B_r) of the punched specimen and the laminated specimen.

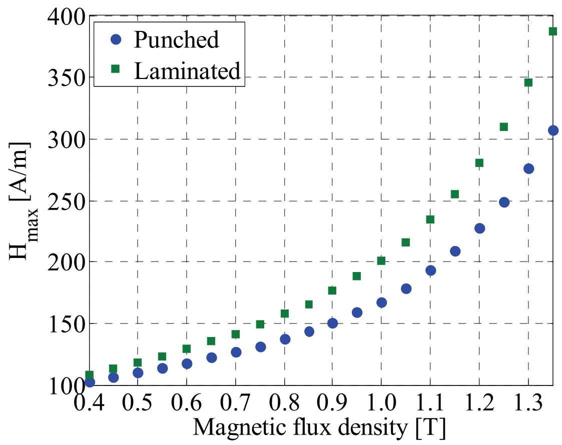


Fig.10. The maximum excitation magnetic field strength (H_{max}) of the punched specimen and the laminated specimen.

Table 1 shows the rate of the magnetic properties of the laminated specimen based on the magnetic properties of the punched specimen. It is understood that all the measured magnetic properties are deteriorated by the laminated process as shown in this table.

The laminated specimen is made from the many punched electrical steel sheets by the pressing process and the gluing process. In addition, it is fixed by the caulking process. It is thought that the processing done by the laminating process is a cause of the degradation of the magnetic properties from the result of this experiment.

Table 1. The change of the measured magnetic properties based on the punched specimen (B_{ex} = 1.35 T).

	W_i	H_c	B_r	H_{max}
Ratio [%]	4.7	3.2	-5.5	26

Conclusions

In this paper, the influence on the magnetic properties caused by the laminating process when the rotating machine was manufactured was examined by using the direct winding method based on the magnetic properties of the punched specimen. Consequently, we have elucidated the following results to evaluate the magnetic properties of the laminated specimen such as the stator core of the rotating machine.

1) These measured magnetic properties showed a special change respectively. Whenever the manufacturing process was passed, most of the magnetic properties were deteriorated. This obviously shows an increase in the building factor.

2) The iron loss after the laminated process increases by about 4.7% compared with the iron loss of the punched specimen.

3) It is thought that the processing such as the pressing process and the caulking process done by the laminating process is a cause of the degradation of the magnetic properties from the result of this experiment.

In the future, in order to evaluate an iron loss of the actual stator core, we should develop accurate evaluation methods.

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REFERENCES

[1] K.Yamamoto, E. Shimomura, K. Yamada, T. Sasaki, Effects of External Stress on Magnetic Properties in Motor Cores, Transactions of The Institute of Electrical En-gineers of Japan, Vol.17-A (1997), No.3.

[2] C. Kaido, H. Moge, K. Hanzawa, The Effect of Short Circuit between Laminated Steel Sheets on the Performance of Lamination Core of Motor, Transactions of The Institute of Electrical Engineers of Japan, Vol.123-A (2003), No.9, pp.857-862.

[3] T. Takabayashi, Y. Ishihara and T. Todaka, Study of Measurement Method of Ring Specimen using the yoke, The Papers of Technical Meeting on Magnetics, IEE Japan (2005) , MAG-05-112, p.51-56.

[4] K. Senda, M. Kawano and M. Ishida , Analysis of Core Magnetic Property Deterioration by Interlocking, The Papers of Technical Meeting on Magnetics, IEE Japan (2005), MAG-05-42, p. 21-26.

[5] M. Oka, O. Nakazaki, T. Kanda and M. Enokizono, Measurement of Material Properties of Actual Electrical Steel Stator Core to Achieve High Efficiency of Rotating Machines, Bulletin of Topical Symposium of the Magnetic Society of Japan (2008), pp. 27-32.

[6] M. Oka, T. Kanada, T. Kai, M. Enokizono, Iron Loss Evaluation for Improvement of a Building Factor of a Rotating Machine, Proceedings of 21th Symposium on Electromagnetics and Dynamics (2009), pp. 311-316.

[7] M. Oka, T. Kai, M. Enokizono, Examination of the Iron Loss Evaluation Method for the Actual Stator Core, Proceedings of 18th Symposium on Electromagnetics and Dynamics (2009), pp. 147-150.

[8] M. Oka, T. Kai, M. Enokizono, Influence of Processing on the Magnetic Properties of the Actual Stator core, Proceedings of 22th Symposium on Electromagnetics and Dynamics (2010), pp. 386-391.

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