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The body can be viewed from the next page.

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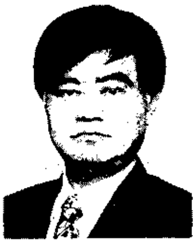
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1 Introduction

The total performance of inverter power supplies has improved dramatically as a result of the development of control methods, higher performance in semiconductors, and higher speed, higher integration, and less expensive integrated circuits. This has made it possible to use the inverter drive method in a wide range of rotating machinery which requires smaller and/or variable speed drives. In line with these trends, magnetic loss under nonsinusoidal wave form excitation, including lower order harmonics, has been studied[1,2], and loss under inverter excitation[3,4] and the distribution of the rotating magnetic flux in the stator and rotor core of rotating machines have been investigated[5]. In particular, it has been reported that iron loss in electrical steel sheets is higher under inverter excitation, albeit slightly, than under sinusoidal wave form excitation at the same frequency as the basic frequency in inverter excitation[3]. However, there have been few systematic reports regarding the influence of core materials on motor efficiency as such under inverter excitation. The authors previously examined the influence of core materials on the efficiency of single-phase motors under sinusoidal wave excitation, and found that there is an optimum Si content of the core material which is inversely related to the designed flux density of the motor[6].

The aim of the present work is to show the information to determine the optimum core material which will yield the maximum motor efficiency under inverter excitation. For this purpose, three-phase induction motors were constructed using various materials, and their characteristics were investigated.

2 Experimental Method

2.1 Specifications of Test Motors and Measuring Device

The specifications of the motors are described below. Because the influence of rotor core making accuracy on motor characteristics is greater than the influence of the material, the measurements in these experiments were preformed using the same commercially-available rotor. The material was varied only in the stators in order to investigate the influence of materials. Three stators were made by punching electrical steel sheets with a die. After winding of copper wires around the stator teeth, motor characteristics were evaluated. The windings were then removed, and the stators were annealed for 2 h at 750°C in nitrogen gas to investigate the influence of annealing. After annealing and winding of the stators, magnetic properties of the motors were measured again.

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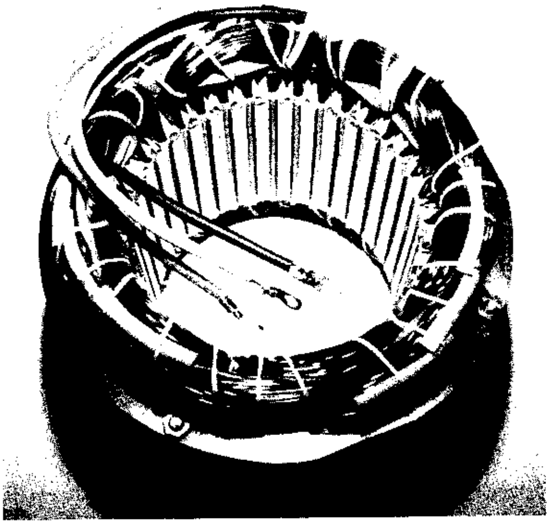

Photo 1 Appearance of tested stator core

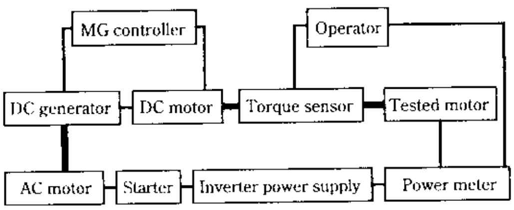

Fig. 1 Block diagram of apparatus for measuring motor efficiency

(1) Electrical Specifications
3-phase, 6-pole; Rated 120 Hz - 120 V - 400 W
(2) Winding
3-phase, 6-pole star wiring; 150 turns/phase
(3) Dimensions
Stator
Outer diameter: 140 mm, Inner diameter: 84 mm
Stacking thickness: 66.3 mm; 36 slots
Rotor
Outer diameter: 83.4 mm
Stacking thickness: 66.3 mm; 44 slots

A specimen motor is shown in **Photo 1**. **Figure 1** shows a block diagram of the measuring device. The inverter power supply comprised a freely controllable wave form generator and a power amplifier, and had a 3-phase output of 1 500 W, a maximum inverter frequency of 400 Hz, and a maximum carrier frequency of 20 kHz.

2.2 Measurement Conditions

The PWM (pulse width modulation) voltage was used as inverter wave. In general, the rotating speed of induction motors is controlled by changing the synchronous rotation (Ns = $120f/p$, p: number of poles) by changing the basic frequency (f) of the power supply using the inverter. The basic frequency of the PWM inverter wave is changed by switching on and off the high harmonic which is called the carrier wave. Sasaki et al.[3] made a detailed investigation of the influence of the carrir wave on magnetic loss under PWM inverter wave excitation. According to their findings, if the basic wave voltage and the carrier wave voltage are substantially the same, as is normally the case, increasing the frequency of the carrier wave will reduce the iron loss of the electrical steel sheet. In these experiments, in order to decide the frequency of the carrier wave to be used, the influence of the carrier wave frequency on actual motor efficiency was investigated as a preliminary experiment. The results are shown in **Fig. 2**. In the case of a basic wave of 60 Hz, higher efficiency could be obtained by increasing the frequency of the carrir wave, as reported by Sasaki et al.[3] However, there was little change in efficiency at carrir wave frequencies of 2 400 Hz and over. Accordingly, a frequency 40 times the basic frequency was adopted for the carrir wave in these experiments.

Various conditions of measurement are conceivable depending on the manner in which the motor is driven. Here, the relationship between the inverter frequency and voltage was adopted on the assumption that drive power would be required in the low speed region. The results are shown in **Table 1**, which also shows the design flux density of the stator teeth. At the same time, in order to investigate the influence of design flux density, the copper loss was measured under the condition that B was varied from 1.34 to 2.0 T at the basic frequency of 60 Hz. The maximum efficiency in the vicinity of the synchronous rotating speed at the respective basic power supply frequencies was adopted as the motor efficiency. In addition to evaluation at this maxi-

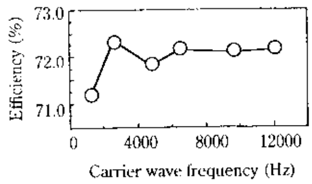

Fig. 2 Effect of carrier wave frequency on efficiency of motor

Table 1 Motor driving condition

Inverter freq. (Hz)	Carrier freq. (Hz)	Voltage (V)	Rotation (rpm)	Flux density (T)
30	1 200	55	600	1.84
60	2 400	80	1 200	1.34
60	2 400	110	1 200	1.84
60	2 400	120	1 200	2.00
120	4 800	120	2 400	1.00
240	9 600	200	4 800	0.84
300	12 000	240	6 000	0.80

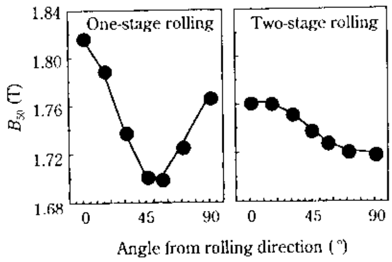

Fig. 3 Anisotropy of non-oriented Si steel sheets

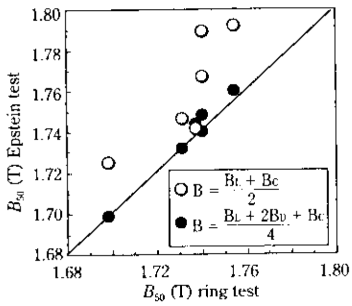

Fig. 4 Relation between ring test and Epstein test for non-orientated Si steel

mum efficiency point, efficiency was also measured under various drive conditions, and an efficiency map was prepared using a spline.

2.3 Evaluation of Properties of Core Materials

Non-oriented electrical steel sheets which are used as the material of motor cores show some, albeit slight, degree of magnetic anisotropy. **Figure 3** shows an example of the dependence of the magnetic flux density B_{50} of the electrical steel sheets, of which there are at least two kinds: one with minimum flux density crosswise and the other with a minimum value in the diagonal direction (D). It follows that the ring properties, which correspond to the average properties in the full circumferential direction, are preferable to measurements with Epstein test pieces cut from the rolling direction (L) and cross rolling direction (C) in evaluating materials for motors. However, an excessive amount of work is required for winding, etc. when measuring ring properties. The authors therefore demonstrated in a previous work that the same level of evaluation, as with ring property measurement, can be achieved by measuring a diagonal direction (D) Epstein test piece, in addition to the L and C direction pieces, and calculating and average for four directions as $(L + 2D + C)/4$ (**Fig. 4**)[6]. This method was used in evaluating the materials in this report.

Figure 5 shows the influence of the Si content, sheet thickness, and stress relief annealing on the magnetic properties of the materials used in these experiments. In

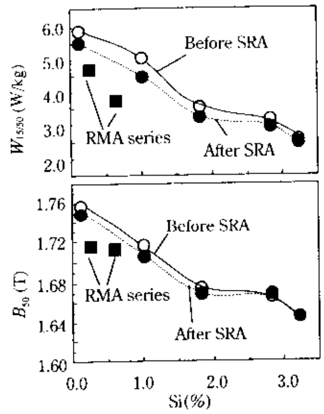

Fig. 5 Effects of Si content and stress relief annealing (SRA) on material characteristics

JIS grade material expressed by open circles, Si reduces the iron loss because Si also reduces eddy current loss by increasing resistivity. On the other hand, the B_{50} of the material is decreased when the Si content is increased because Si reduces the saturation magnetic flux density. Stress relief annealing has no significant effect on the B_{50} of high-Si materials, but does reduce the iron loss. RMA series shown by the square symbols in Fig. 5 show much less iron loss than JIS grade after stress relief annealing.

3 Experimental Results and Discussion

Figure 6 shows the influence of the Si content and the PWM frequency and stress relief annealing on motor efficiency. As described earier, the magnetic flux density is designed to change when the PWM frequency is altered. With all the materials, motor efficiency improves when stress relief annealing is performed. Irre-

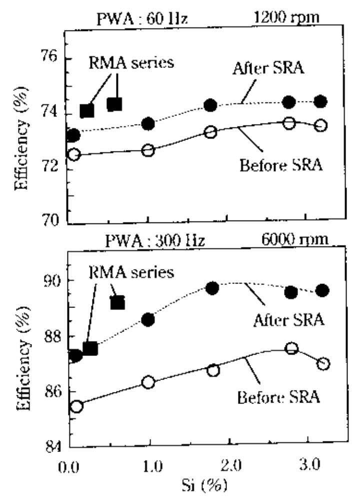

Fig. 6 Effect of Si content of core materials, SRA and PWM frequency on motor efficiency

spective of stress relief annealing, motor efficiency tends to decrease with the excitation frequency in the lower frequency region. There is little influence of the Si content of the material in the lower frequency region. In contrast, it is large in the higher frequency region, and the motor efficiency becomes maximum when the Si content of the core material is about 1.8%. The efficiency of motors using RMA is as great as those using high Si material both at low and high frequencies.

Figure 7 shows the motor iron loss and copper loss after stress relief annealing. The motor copper loss increases and iron loss decreases with Si content of the material at low frequency and low rotation speed. At high frequency and high rotation speed, the iron loss becomes dominant and decreases with Si content of the material, while the copper loss is small and there is little change due to Si content. The iron loss of motors using RMA is relatively small. Although a slip should be considered in discussing the efficiency of AC induction motors, the slip is neglected here for simplicity. The motor efficiency can be expressed as follows[7]

$$\begin{aligned}\eta &= \text{Output}/(\text{Output} + \text{Copper loss} + \text{Iron loss})\\ &= nT/(nT + k_c R I^2 + k_i n^k)\\ &= 1/(1 + k_c R I/NAB_m n + k_i n^{k-1}/NAB_m I) \cdots (1)\end{aligned}$$

where n, R, $T = NAB_m I$, I, N, A and B_m are rotating speed, winding resistance, torque, current, number of winding cross section of the core and designed flux density, respectively. k, k_i and k (> 1.0) are the constants obtained empirically from the motor shape, etc.

It is clear from the equation that copper loss and iron loss are dominant when n is small and large, respectively. Therefore the efficiency of the motor is low at low rotation speed due to large copper loss, and at extremely high rotation speed due to large iron loss. However in the normal rotation speed region, the efficiency increases with rotation speed because the decrease of copper loss is larger. The change of motor efficiency is restrained at intermediate rotation speed of 1 200 rpm (PMW frequency: 60 Hz). This is because iron loss change in this region is compensated by the change of copper loss, though the copper loss is dominant as shown in Fig. 7. The increase of copper loss with Si content is due to that high Si material has poor magnetic permeability, as shown in Fig. 5, and the motor permeability is proportional to the material permeability. As predicted by Eq. (1), copper loss is small and iron loss is dominant at the rotation speed of 6 000 rpm (PMW frequency: 300 Hz). The iron loss of the motor in this region decreases with Si content of the core material reflecting the material iron loss.

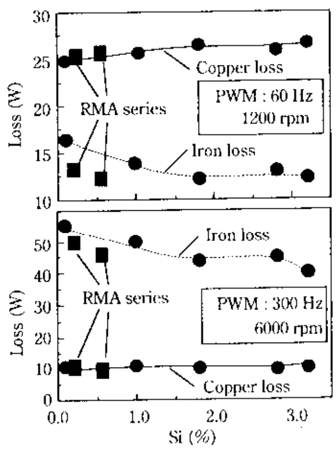

Fig. 7 Effect of Si content on iron loss and copper loss of motor after SRA

With all the materials, motor efficiency improves when stress relief annealing is performed. However, the improvement in efficiency is greater in the high-frequency region than that in the low-frequency region. This is because the improvement of core loss by stress relief annealing is larger in the high frequency region, and also the designed flux density is optimized so as to be higher at the low frequency region and lower at the high frequency region. Since the induced strain by punching deteriorates the core loss more at the low flux density region, core loss at the low flux density region, *i.e.*, at the high frequency region is considered to be improved more remarkably by stress relief annealing.

Figure 8 shows efficiency map of the motor using 3.2% Si material before and after stress relief annealing. As we can see, the efficiency was improved by stress relief annealing not merely at the maximum efficiency points but in the entire driving region.

From Eq. (1), it should be possible to obtain high efficiency by increasing NAB_m. However, there is a practical limit because it is necessary to increase the motor capacity in order to increase flux and the number of windings.

Figure 9 shows the effect of Si content and designed flux density on the motor copper loss at the rotation speed of 1 200 rpm (PWM frequency: 60 Hz). **Figure 10** shows the effect of Si content on the flux density of core material. Comparing these two figures, it is clear that when the designed flux densely is low, the copper loss of high Si core material is lower, responding to its relatively high flux density at low magnetic field. However,

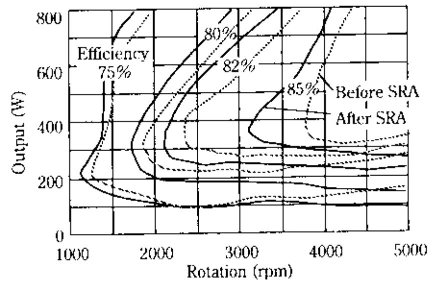

Fig. 8 Efficiency map of motor using 3.2% Si material before and after SRA

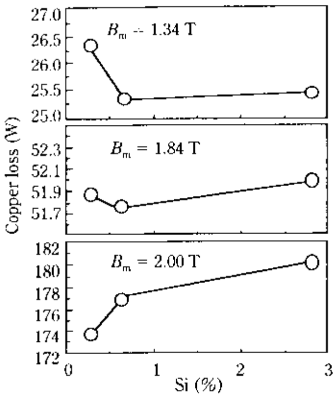

Fig. 9 Effect of design flux density B_m on copper loss of motor

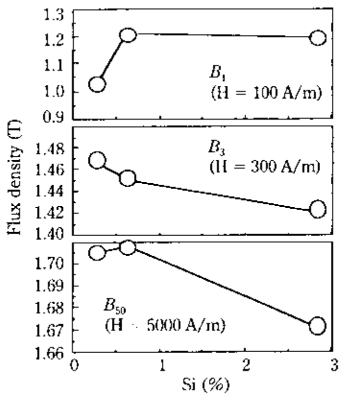

Fig. 10 Effect of Si content and magnetizing force on flux density of core material

when the designed flux density is high, the copper loss of low Si material is rather small because low Si material has high flux density at high magnetic field. Therefore it was found that the optimum Si content of the material varies depending on the designed flux density.

Figure 11 shows the effect of sheet thickness of 1.8% Si material on the motor efficiency. The efficiency increases with decreasing material thickness regardless of rotation speed. This is because iron loss of the motor using thinner material was improved by reducing eddy current loss. Since the flux density of the material is not generally affected by the reduction of material thickness, the change of copper loss is considered to be small. Therefore, reducing material thickness is one of the best ways to improve motor efficiency.

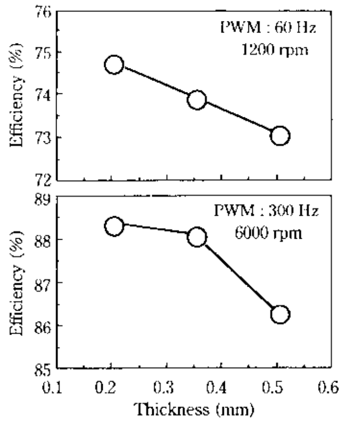

Fig. 11 Effect of material thickness on motor efficiency (1.8%Si steel)

4 Conclusion

The influence of core material magnetic properties, iron loss, sheet thickness, and stress relief annealing on the efficiency, iron loss and copper loss of 3-phase 6-pole 400 W inverter drive motors was investigated, with the following results.

(1) The effect of material Si content on the motor efficiency was small when PWM frequency and rotarion speed were low.

(2) The efficiency increased with Si content in high rotation speed region because the iron loss ratio in motor loss increased considerably in this region.

(3) An optimum Si content varied depending on the designed flux densty. Therefore, it is important to choose a core material suitable for the motor design.

(4) Efficiency is improved by reducing the sheet thickness of the core material.

(5) Regardless of the material, stress relief annealing improves motor efficiency particularly in the high frequency region.

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