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Magnetic Properties of Commercially Produced Fe–6.5wt% Si Sheet

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Abstract. The commercial scale production of Fe–6.5wt% Si sheet has been successfully developed. Fe–6.5wt% Si sheets ranging in thickness from 0.1 to 0.5 mm can be manufactured in coil form with a maximum width of 400 mm.

The following magnetic properties have been achieved.

1. The maximum permeability is about 10 times higher than that of the conventional nonoriented silicon steel, and could be doubled by magnetic field annealing.
2. The core losses are less than half of the conventional nonoriented silicon steel's, and even less than the grain oriented silicon steel's at a frequency range of over 400 Hz.
3. The coefficient of magnetostriction is extremely small (6×10^{-7}). It is less than one-tenth of the conventional nonoriented silicon steel's.

Fe–6.5wt% Si sheet should be used extensively as an electric and electronic material, owing to its own supreme soft magnetic properties. For example, this sheet is good for use in motor cores or high frequency transformer cores, supreme magnetic shields, and so on.

The details of the magnetic properties of Fe–6.5wt% Si sheet and some applications to electric devices are described.

INTRODUCTION

It has been well known that Fe–6.5wt% Si alloy exhibits excellent soft magnetic properties [1]. Indeed, it is perfectly true that sheet of this alloy has been desired as a material for electric or electronic apparatuses and devices. Therefore, many experimental and industrial approaches of sheet production have been explored [2,3]. However, no one has succeeded in manufacturing Fe–6.5wt% Si sheet on account of this alloy's poor ductility. Consequently, the currently available information on Fe–6.5wt% Si sheet from 0.1 mm to 0.5 mm thickness has been recognized as short of useful, although there is a great deal of information on the cast products and the thin foils produced by the rapid quenching process [4].

Two methods of commercial scale production of Fe–6.5wt% Si sheet have been successfully developed by the NKK Corporation: the rolling process and the chemical vapor deposition process. Presently, manufactured sheets from 0.1 mm to 0.5 mm thickness can be provided in coil form of 400 mm width. These manufactured sheets are nonoriented.

The magnetic properties of our Fe–6.5wt% Si sheet are here investigated and compared with conventional silicon steel and discussed. Furthermore, workability and some practical applications are examined.

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MAGNETIC PROPERTIES

Experimental Procedures

Figure 1 shows one of the coils of Fe–6.5wt% Si sheet produced by the rolling process. The thickness of this coil is 0.5 mm and the width is 200 mm. The chemical compositions of this coil are shown in Table 1. The content of impurities was reduced as much as possible except for Si. The real amount of Si content is slightly more than 6.5%, because 6.65wt% Si exhibits the best magnetic properties, as shown in Figure 2.

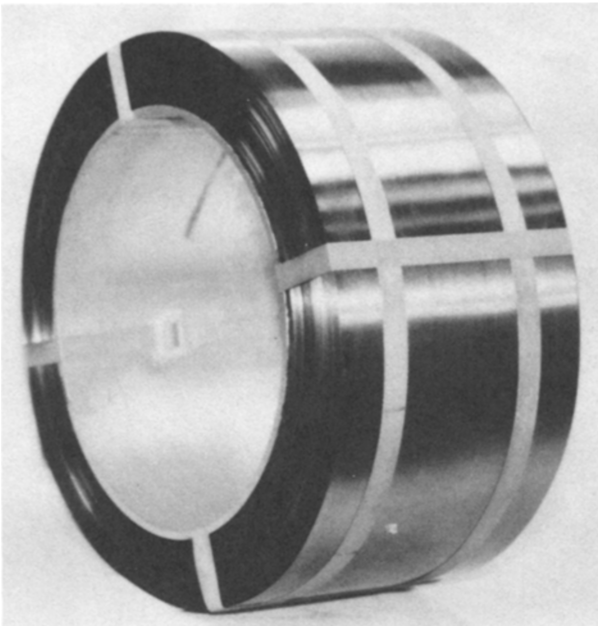

Fig. 1. Fe–6.5wt% Si sheet of 0.5 mm thickness produced by rolling process.

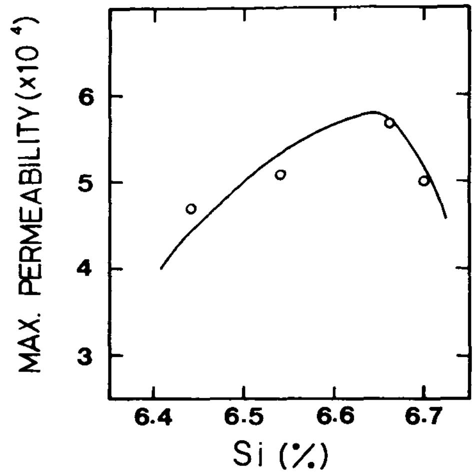

Fig. 2. Influence of Si content on relative maximum permeability.

Figure 3 shows the 0.1 mm thick sheet produced by the chemical vapor deposition (CVD) process. The chemical compositions and the magnetic properties of this coil are identical to those of the coil produced by the rolling process. In NKK, Fe–6.5wt% Si sheets of over 0.35 mm thickness are manufactured by the rolling process and sheets of under 0.35 mm thickness manufactured by the CVD process.

In this work, 0.1, 0.3, and 0.5 mm thick sheets of Fe–6.5wt% Si alloy were examined, and the same thickness sheets of conventional nonoriented silicon steel (JIS C 2552; 50A270), grain oriented silicon steel (JIS C 2553; 30P110) and PB-PERMALLOY® (JIS C 2531)[1] were used for comparison.

The magnetic properties of samples were measured with the automatic dc or ac B–H curve tracers, Epstein, and the vibrating sample magnetometer. On the measurement with the B–H curve tracer, the ring samples, whose inner and outer diameters were 10 and 20 mm respectively, were cut by electrical discharge machines. The ratio of outer-to-inner diameter of the ring sample selected was relatively large, because the sample sheet had large crystal grain. After cutting, the samples were annealed at 800° C for 30 min to remove residual strain.

Table 1. Chemical Composition of a Sample, wt%

C	Si	Mn	S	P
0.002	6.660	0.010	0.001	0.004

[1]PB-PERMALLOY®: Nickel iron soft magnetic alloy sheet (JIS C 2531).

dc Magnetic Properties

Figure 4 shows the dc hysteresis loop of Fe–6.5wt% Si sheet of 0.5 mm thickness, which was annealed at 1200° C for 1 hr. The coercive force of Fe–6.5wt% Si sheet is 6 A/m. The relative maximum permeability is 58,000, which is about 10 times higher than that of the nonoriented silicon steel. The induction of Fe–6.5wt% Si sheet is 1.27 T at 800 A/m, which is slightly lower than that of conventional silicon steel

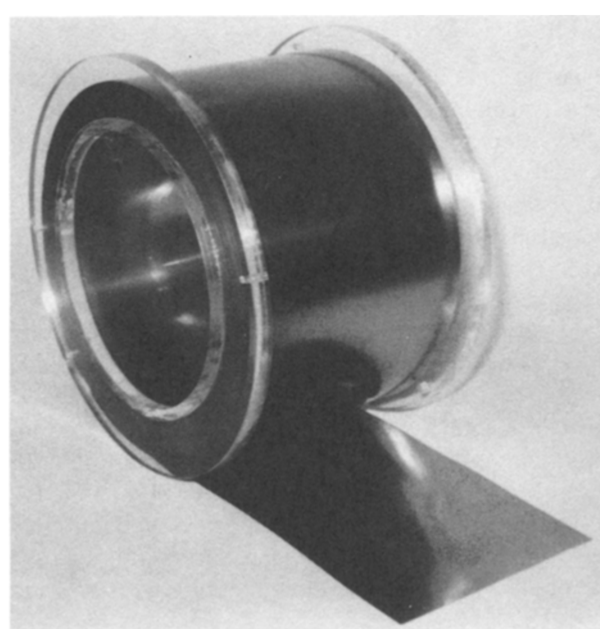

Fig. 3. Fe–6.5wt% Si sheet of 0.1 mm thickness produced by CVD process.

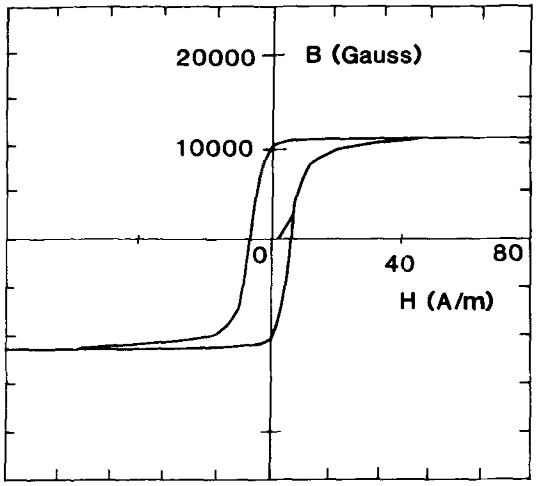

Fig. 4. dc hysteresis loop of Fe–6.5wt% Si sheet of 0.5 mm thickness.

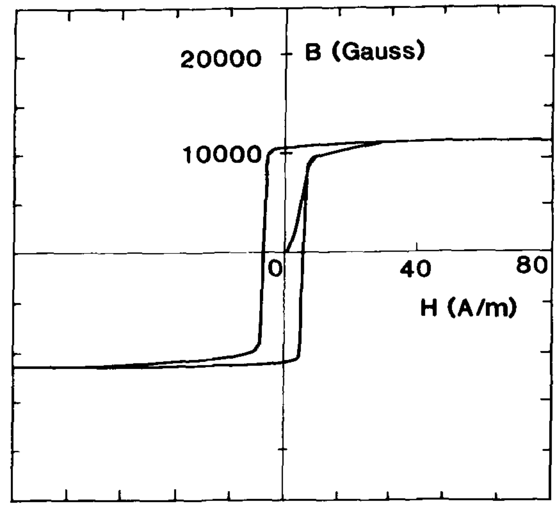

Fig. 6. dc hysteresis loop of Fe–6.5wt% Si sheet of 0.5 mm thickness after magnetic field annealing.

as a result of its higher Si content. However, the saturation induction measured by the vibrating sample magnetometer is 1.83 T, which is sufficiently high. Lastly, the hysteresis loss is about 30% of conventional silicon steel's, compared with Figure 5, which shows the dc hysteresis loop of nonoriented silicon steel.

Furthermore, Fe–6.5wt% Si sheet was annealed in the magnetic field; the hysteresis loop therefore could be made rectangular, and obviously higher permeability resulted, as shown in Figure 6. Basically, the relative maximum permeability is 98,000, which is much higher than that of grain oriented silicon steel.

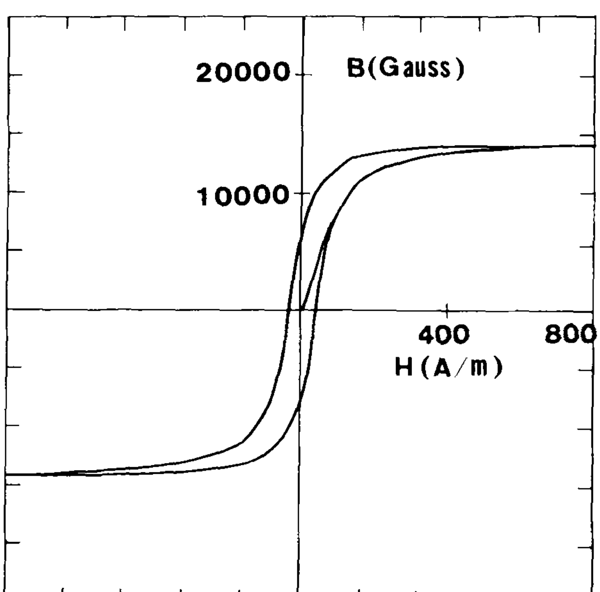

Fig. 5. dc hysteresis loop of nonoriented silicon steel of 0.5 mm thickness.

On the other hand, the magnetic properties of conventional silicon steel could not be remarkably improved by the magnetic field annealing.

ac Magnetic Properties

Fe–6.5wt% Si sheet exhibits not only the good dc magnetic properties mentioned previously, but also excellent ac properties. Especially, this sheet exhibits better properties than the conventional silicon steel sheet does in the high frequency region.

In Figure 7, the ac-hysteresis loops at 10 kHz of the 0.5 mm thick sheet of (A) Fe–6.5wt% Si alloy, (B) nonoriented silicon steel and (C) PB-PERMALLOY® are shown. The loop of Fe–6.5wt% Si sheet is clearly the smallest on account of the low hysteresis loss as shown in Figure 4 and the low eddy current loss which is achieved by high electric resistivity. The electric resistivity of Fe–6.5wt% Si alloy is 82 $\mu\Omega$ cm which is about two times higher than that of conventional silicon steel or PB-PERMALLOY®.

Figure 8 shows the core losses from 50 Hz to 100 kHz. Fe–6.5wt% Si sheet of 0.1 mm thickness exhibits appreciably lower core losses.

Figure 9 shows the effective permeabilities of 0.1 mm thick sheet of (A) Fe–6.5wt% Si alloy and (B) conventional nonoriented silicon steel. Higher effective permeability is achieved obviously. Figure 10 shows the effective permeabilities of Fe–6.5wt% Si sheet of (A) 0.1 mm, (B) 0.3 mm, and (C) 0.5 mm thicknesses. As a result, the effective permeability of 0.1 mm nonoriented silicon steel sheet is recognized to be equal to that of 0.3 mm thick sheet of Fe–6.5wt% Si alloy.

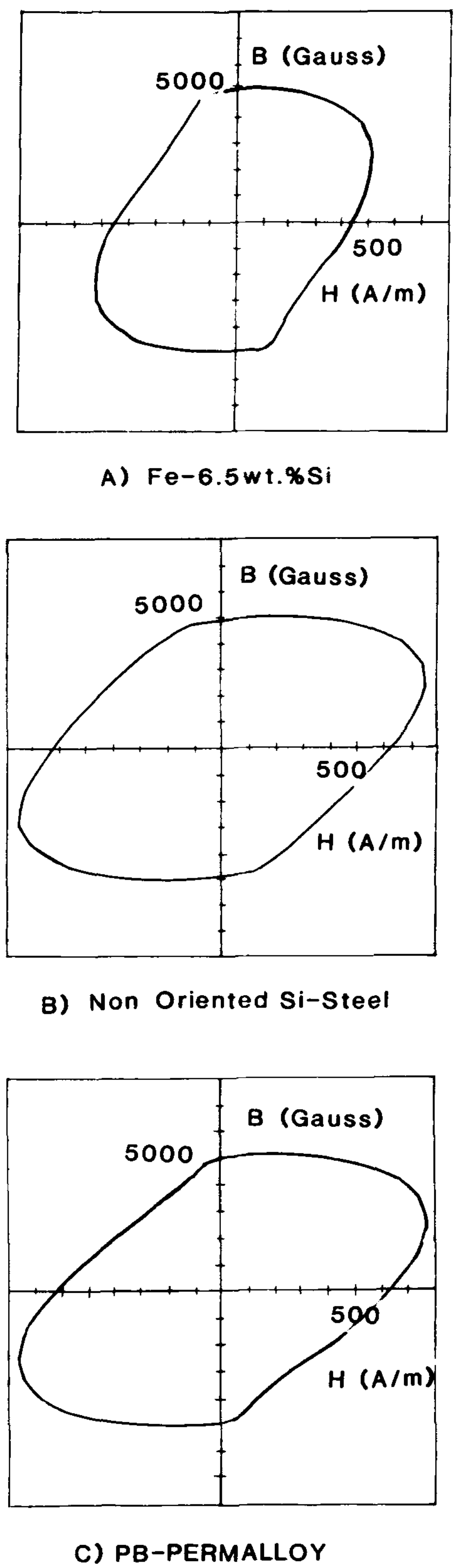

Fig. 7. ac hysteresis loops at 10 kHz of the 0.5 mm thick sheet of (A) Fe–6.5wt% Si, (B) nonoriented silicon steel, and (C) PB-PERMALLOY®.

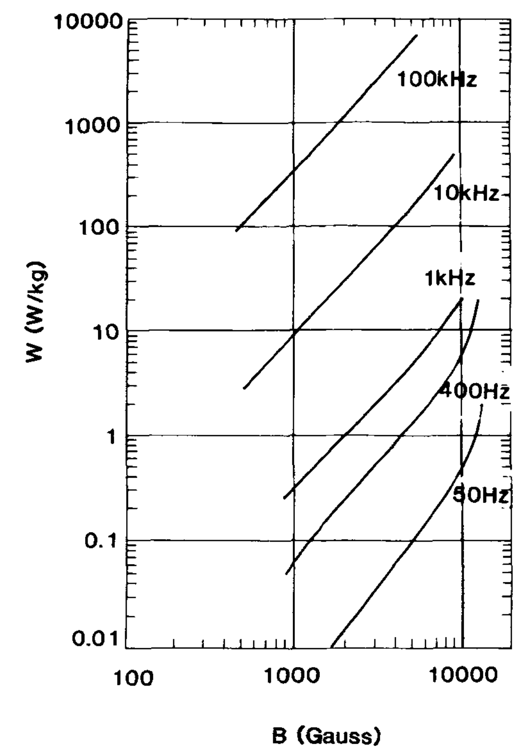

Fig. 8. Core losses from 50 Hz to 100 kHz of 0.1 mm thick sheet of Fe–6.5wt% Si.

Results

Fe–6.5wt% Si sheet has excellent magnetic properties. Table 2 summarizes the physical and mechanical properties of Fe–6.5wt% Si sheet. The small magnetostriction coefficient is one of the essential properties of Fe–6.5wt% Si sheet. Using this sheet, the noise caused by magnetostriction in the transformer core could be expected to be reduced significantly.

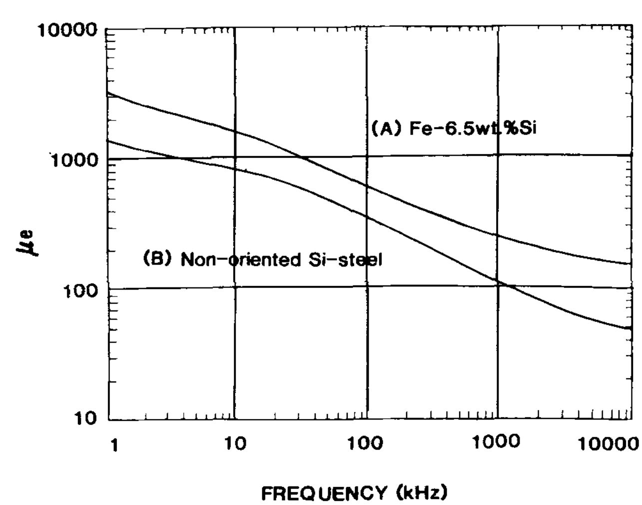

Fig. 9. Effective permeabilities of the 0.1 mm thick sheet of (A) Fe–6.5wt% Si and (B) nonoriented silicon steel.

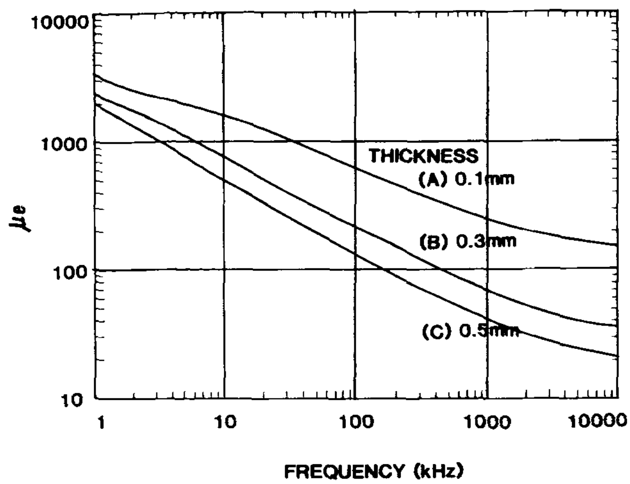

Fig. 10. Effective permeabilities of Fe–6.5wt% Si sheet of (A) 0.1 mm, (B) 0.3 mm, and (C) 0.5 mm.

As shown in Table 3, Fe–6.5wt% Si sheet exhibits better magnetic properties than the conventional silicon steel sheet does; that is,

1. The relative maximum permeability is about 10 times higher than that of nonoriented silicon steel, and could be doubled by magnetic field annealing.
2. The core losses are less than half those of nonoriented silicon steel, and less than those of the grain oriented silicon steel at a frequency range of over 400 Hz.
3. The coefficient of magnetostriction is extremely small (6×10^{-7}). It is less than one-tenth of the nonoriented silicon steel's.

Table 2. Physical and Mechanical Properties of Fe–6.5wt% Si Sheet

Density	7.48 g/cm^3
Electric resistivity	82 $\mu\Omega$-cm
Specific heat (31° C)	0.128 cal/°C·g
Thermal conductivity	0.045 cal/°C·cm·s
Curie point	700 °C
Saturated magnetostriction	6×10^{-7}
Hardness	395 Hv

WORKABILITY

The hardness of Fe–6.5wt% Si sheet is about 400 micro-Vickers as indicated in Table 2. Therefore, the workability of Fe–6.5wt% Si sheet, which is important to produce the electric or electronic apparatuses and devices, was examined.

Stamping

Figure 11 shows one of the results of stamping tests. Fe–6.5wt% Si sheet of 0.5 mm thickness could be stamped into EI core under the conditions indicated in Table 4. Generally speaking, a narrow clearance is necessary to stamp hard materials. As the hardness of Fe–6.5wt% Si sheet is two times higher than that of conventional silicon steel sheet, the narrow clearance shown in Table 4 is necessary.

Furthermore, the stability of stamping is increased by heating the blank sheet. For example, if a 0.35 mm thick sheet of Fe–6.5wt% Si alloy is heated up about 200° C, it could be stamped steadily without cracks.

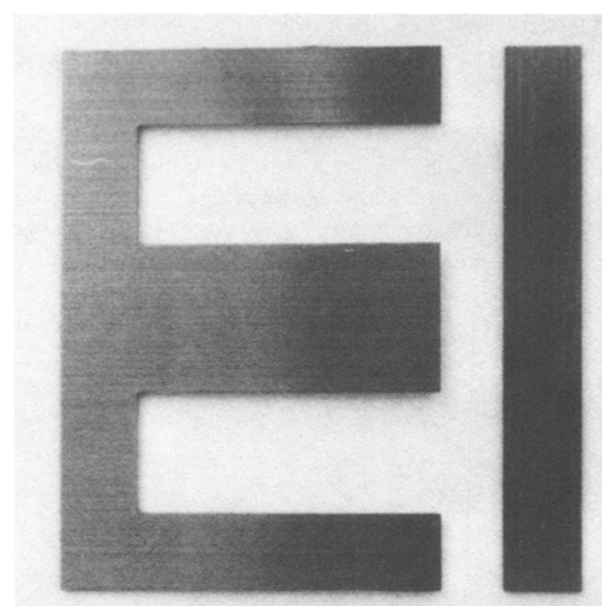

Fig. 11. A sample of EI core stamped out.

Table 3. Comparison of Magnetic Properties between Fe–6.5wt% Si and Conventional Si Steels

	Thickness, mm	B_8, T	Core Loss, W/Kg $W_{10/50}$	Core Loss, W/Kg $W_{10/400}$	Core Loss, W/Kg $W_{2/1K}$	Core Loss, W/Kg $W_{2/10K}$	Relative Permeability
Fe–6.5wt% Si	0.10	1.22	0.51	5.98	0.96	32.5	31,000
	0.30	1.27	0.49	10.0	1.80	74.4	40,000
	0.50	1.27	0.58	15.6	2.80	106	58,000
Nonoriented 3.0% Si steel	0.50	1.42	1.36	27.1	4.84	180	7,700
Grain Oriented 3.2% Si steel	0.30	1.93	0.35	10.5	2.70	150	74,000

Table 4. Conditions of Stamping Test

Machine	Capacity	25 ton
	Stroke	15 mm
	Strokes/min	350
Tool	Clearance	5%
	Punch	Sintered hard alloy
	Die	Tool steel

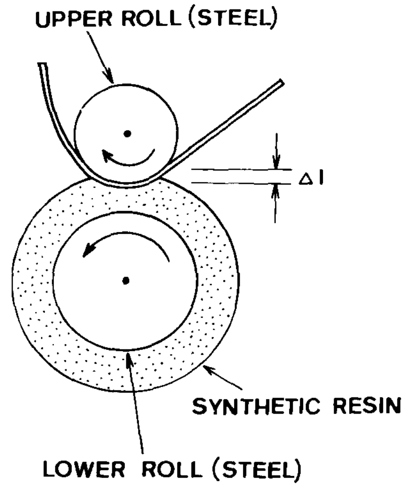

Fig. 13. Schematic diagram of two-roller bender.

Roll Forming

Figure 12 shows a cylinder made of Fe–6.5wt% Si sheet of 0.35 mm thickness by using a two-roller bender, one of which was covered with synthetic resin in order to avoid stress concentration, as shown in Figure 13. This type of bender is commonly used to make electric apparatuses and devices. After roll forming, the cylinder was spot welded. The cylinders of various diameters were obtained by changing the diameter of the upper roll and the thickness of the resin. As an example, under the special condition shown in Figure 14, there was a relation between the maximum processed radius and the sheet thickness.

Results

As an example of the forming of Fe–6.5wt% Si sheet, the possibilities of stamping out and roll forming were discussed. The other processes were also examined and the possibilities of forming were tested and proved, for example, toroidal cores, cut cores, and so on.

It has been clearly proved that Fe–6.5wt% Si sheet has sufficient workability as a material for electric or electronic apparatuses and devices. Further, the workability could be increased by heating sheet or tools.

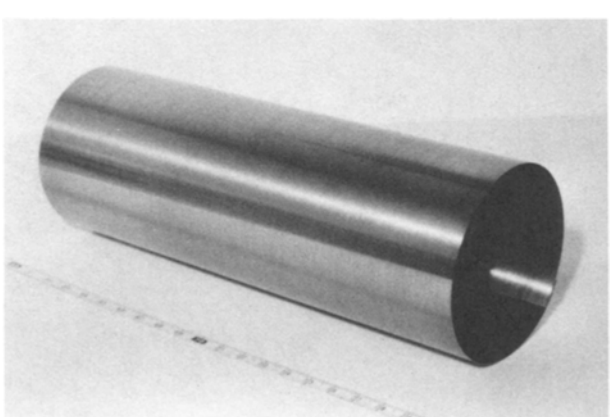

Fig. 12. A sample of cylinder for magnetic shield.

SOME APPLICATIONS

The magnetic properties discussed previously ensure that Fe–6.5wt% Si sheet is adequate for motor cores or transformer cores in high frequency use and for magnetic shields. As examples of application, a dc

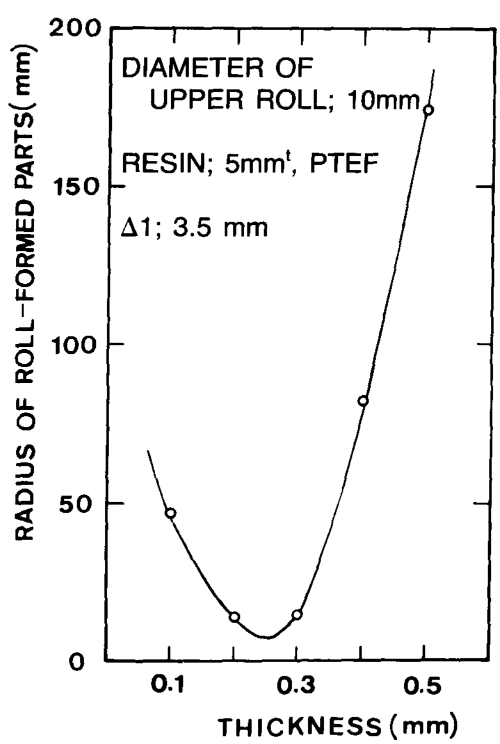

Fig. 14. An example of relationship between maximum bending radius and sheet thickness.

motor and a magnetic shield for a micromotor are studied.

dc Motor

Two dc motors, with identical power losses due to a mechanical cause, were tested. Fe–6.5wt% Si sheet and the conventional nonoriented silicon steel were used for the rotor. The no-load currents were compared under the same conditions; that is, working voltage of 24 V and revolutions of 2,400 rpm. The result was that the no-load currents of the motor made of Fe–6.5wt% Si sheet was 0.09 mA and that of the other one was 0.14 mA, as shown in Figure 15. Consequently, the no-load power loss was reduced about 40% by using Fe–6.5wt% Si sheet for the motor core.

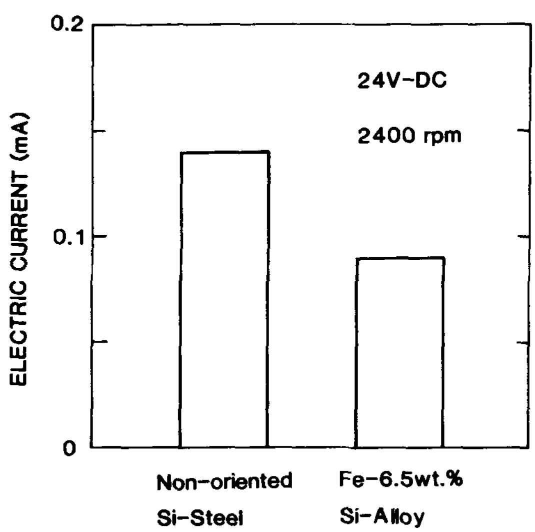

Fig. 15. Comparison of no-load currents of trial dc micromotors.

Magnetic Shield

The magnetic shield of the micromotor which was used in a cassette tape recorder was examined. The leakage flux from the micromotor covered with a magnetic shield was picked up by the magnetic head and amplified by 20 dB and finally analyzed by the signal analyzer, as shown in Figure 16. Figure 17 indicates the results of the one-turn shield made of 0.3 mm thick sheet of (A) Fe–6.5wt% Si alloy and (B) the commercial grain oriented silicon steel. The noise from the motor shielded with Fe–6.5wt% Si sheet was obviously weaker than that from the other motor. One of the reasons was thought to be the difference of the permeability along the thickness direction.

Results

Some applications, for example, transformer cores, various motors, magnetic sensors, and so on, have also been examined. Good results and performances were obtained. These examinations were done not only by NKK but also by many electric and electronic manufacturers and universities.

CONCLUSION

The commercial scale production of Fe–6.5wt% Si sheet has been successfully developed and can be provided as an industrial material for electric or electronic apparatuses and devices. Fe–6.5wt% Si sheet exhibits superior soft magnetic properties to the conventional silicon steels.

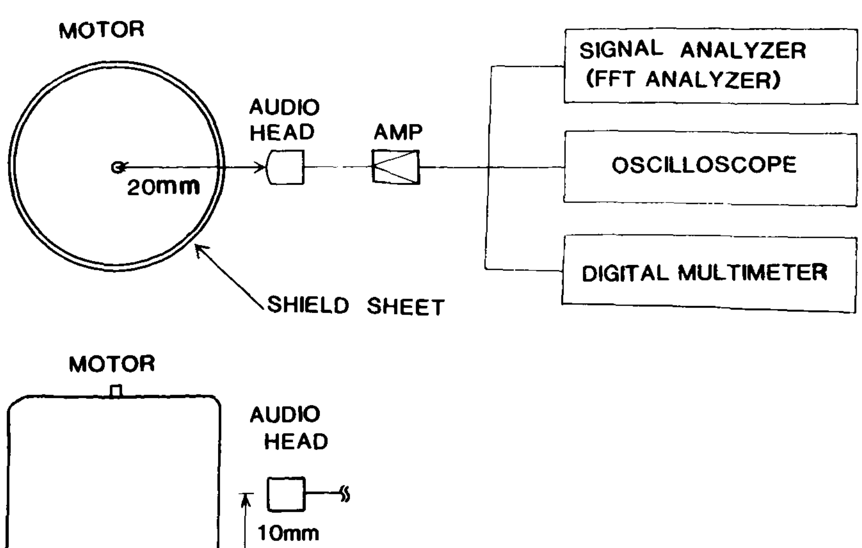

Fig. 16. Experimental procedure of shield effect.

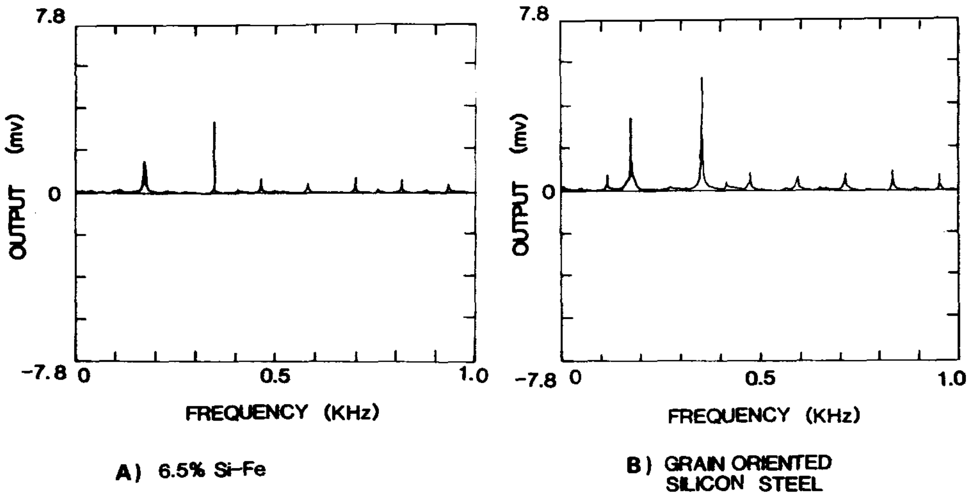

Fig. 17. Comparison of magnetic shield effects.

Lately the electric or electronic apparatuses have a tendency to be used at high frequency. Fe–6.5wt% Si sheet, which has excellent magnetic properties in high frequency regions, can meet the trend.

The processing ability of the material and some applications were examined and good performances were clearly achieved. As a result of this successful development, Fe–6.5wt% Si sheet is now being used by some electric and electronic manufacturers.

REFERENCES

1. R.M. Bozorth, *Ferromagnetism*, D. Van Nostrand Co., p. 30, 1951.
2. G. Facaros and R.G. Aspden, *J. Appl. Phys.*, *33*, p. 1220, 1962.
3. K. Narita and M. Enokizono, *IEEE Trans. on Magnetics*, vol. Mag. 14, p. 258, 1978.
4. N. Tsuya and K.I. Arai, 3M Conf., Cleveland, p. 6A–1, 1978.