JFE TECHNICAL REPORT
No. 6 (Oct. 2005)

Improvement of Permeability and Magnetic Shielding Effect of Pure Iron Magnetic Shield Materials†

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Abstract:

Increasing demand for pure iron magnetic shield materials with an excellent magnetic shielding effect is expected in the future. Therefore, the effect of trace impurity elements on the permeability of pure iron steel sheets for magnetic shield use was investigated, and it was found that Al and S contents on the level of several 10s ppm cause remarkable deterioration of permeability. The results of an evaluation of the magnetic shielding effect using a pure iron steel sheet in which permeability was improved by high purification and precipitate morphology control confirmed that this material has an excellent magnetic shielding effect more than 3 dB higher than that of steel sheets for general forming applications.

1. Introduction

With the popularization of diverse types of electronic equipment, the importance of the problem of the electromagnetic environment has come to be widely recognized, and various studies aimed at satisfying the requirements of a good electromagnetic environment have been carried out[1]. Although magnetic shield materials have long been used by medical institutions and in particle beam accelerators[2], against the background outlined above, expanded demand and a wider range of applications for magnetic shield materials not limited to these traditional fields are expected in the future. The properties required in magnetic shield materials are high permeability at the object magnetic field level and high saturation induction. In comparison with permalloy and grain-oriented silicon steel sheets, pure iron materials are inferior in permeability but offer the advantages of higher saturation induction and lower manufacturing costs[3]. Moreover, because high purification has become possible as a result of recent progress in steelmaking technology, higher permeability has also been achieved.

JFE Steel has commercialized a pure iron-type steel sheet for magnetic shield use, "EFE®," as a material which responds to the above-mentioned magnetic shielding needs while also offering good economy[4]. An outline of the EFE manufacturing process is shown in **Fig. 1**. High permeability is achieved in EFE by high purification in the steelmaking stage and precipitate morphology control in the hot rolling stage. Moreover, reduction of impurities is not only effective for improving saturation induction, but in combination with a precipitate control technology in the hot rolling stage, also makes it possible to improve permeability in low mag-

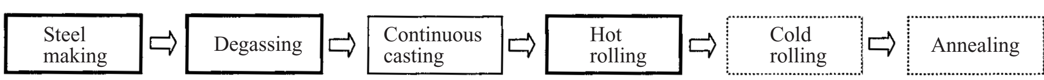

Fig. 1 Manufacturing processes of EFE steel sheet

† Originally published in *JFE GIHO* No. 8 (June. 2005), p. 22–25


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Table 1 Chemical composition of specimen

(mass%)

Mark	C	Si	Mn	P	S	solute Al	N
Al-1	0.002 3	0.01	0.17	0.010	0.003 5	<0.000 5	0.002 6
Al-2	0.002 4	0.01	0.17	0.010	0.003 6	0.003 1	0.002 4
Al-3	0.002 1	0.01	0.17	0.011	0.003 5	0.039	0.002 5
S-1	0.002 0	0.01	0.16	0.010	0.001 8	<0.000 5	0.003 5
S-2	0.002 1	0.01	0.15	0.010	0.004 1	<0.000 5	0.003 0
S-3	0.002 1	0.01	0.15	0.010	0.012	0.000 5	0.003 1
S-4	0.002 1	0.01	0.15	0.011	0.018	0.001 3	0.002 6

netic fields. This paper describes the key points in the material design for achieving high permeability in EFE, and presents the results of an evaluation of the magnetic shielding effect of this material.

2. Experimental Procedure

2.1 Effect of Al and S Contents on DC Magnetic Properties

Specimens were prepared as follows in order to study the effect of trace impurity elements on permeability in low magnetic fields of the terrestrial magnetic field level (H=28 A/m). Using electrolytic iron, 50 kg ingots with various contents of Al and S were melted by laboratory-scale vacuum melting. The specimens were hot rolled to a thickness of 2.5 mm, pickled, and cold rolled to 0.9 mm in the laboratory, followed by recrystallization and grain-growth annealing at 750°C for 60 s. The chemical compositions of the specimens are shown in **Table 1**. To evaluate magnetic properties, ring-shaped test pieces (inner diameter: 33 mm, outer diameter: 45 mm) were taken in accordance with JIS C 2531 and wound with 100 turns each of an excitation coil and pickup coil. Magnetic properties were then measured using an automatic Epstein measuring device (manufactured by Metoron, Inc.).

2.2 Evaluation of Magnetic Shielding Effect

EFE is a type of steel which was designed to show an excellent magnetic shielding property by taking advantage of high purification technology and precipitate morphology control technology. Model shield boxes were prepared using EFE and steel sheets for general forming applications as a comparison material, and their shielding effects were evaluated.

The pure iron steel sheet for magnetic shielding use, EFE (thickness: 0.8 mm) and steel sheets (thickness: 0.8 mm, 1.2 mm) were used as specimens. For measurement of the magnetic properties of the base materials, ring-shaped test pieces (inner diameter: 33 mm, outer diameter: 45 mm) were taken in accordance with JIS C 2531 and wound with 100 turns each of an excitation coil and pickup coil. Magnetic properties were then measured using an automatic Epstein measuring device (Metoron, Inc.). Evaluation of the magnetic shielding effect was performed as follows. Using the three types of specimens, square-shaped shield boxes with side dimensions of 200 mm were prepared. Next, as shown in **Fig. 2**, the shield box was set inside a Helmholtz coil positioned in a magnetic shielding room, and the external field generated by the Helmholtz coil and the internal field at the center position in the shield box were measured. The magnetic shielding effect (S) was evaluated using Eq. (1).

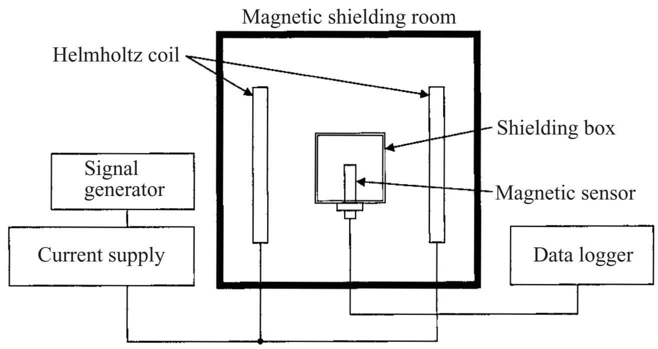

Fig. 2 The measurement method of the magnetic shielding effect

$$S = 20\log\{(\text{external field}) / (\text{internal field})\} \cdots (1)$$

An MAG-03MC sensor (manufactured by Bartington Instruments Ltd.) was used as the magnetic sensor in this experiment. The sensor was inserted into the shield box through a ϕ25 mm hole in one side of the box.

3. Experimental Results

3.1 Effects of Al and S Contents on DC Magnetic Properties

The effects of the Al content and S content on the

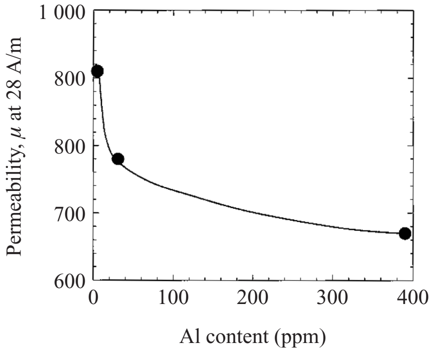

Fig. 3 Effect of Al content on permeability (S: 35 ppm)

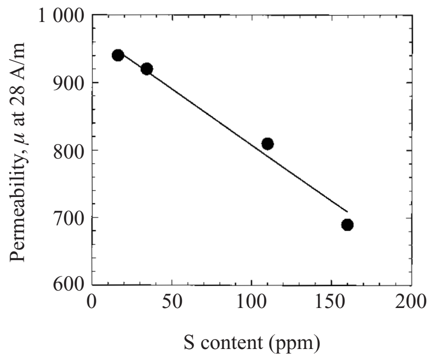

Fig. 4 Effect of S content on permeability (Al: <5 to 13 ppm)

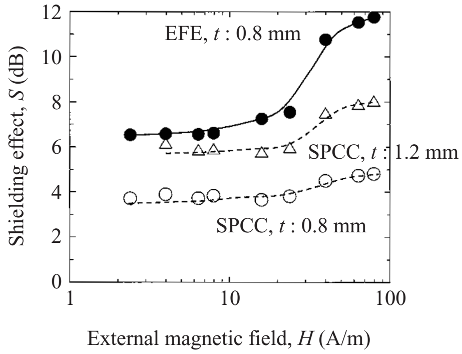

Fig. 5 Magnetic shielding effect (DC)

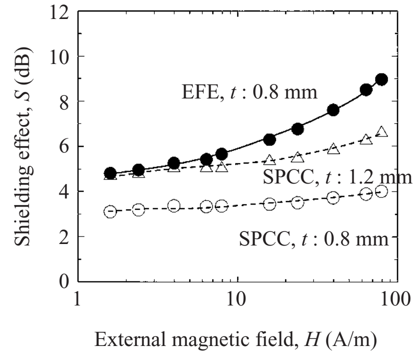

Fig. 6 Magnetic shielding effect (50 Hz)

permeability of pure iron at a field level equivalent to the terrestrial magnetic field are shown in **Figs. 3** and **4**, respectively. With both Al and S, increased permeability can be observed as the content decreases. With Al, permeability is reduced remarkably in comparison with Al-free steel, even at Al levels as low of 30 ppm. On the other hand, with S, permeability decreases in a basically linear manner as the S content increases within the composition range from 35 ppm to 180 ppm. As it has also been reported that the grain growth property increases remarkably when S is reduced to 10 ppm or less[5)], improved permeability can be expected by further reduction of S below 35 ppm.

The results of the present study revealed that a high performance material with permeability of 800 or higher at the terrestrial magnetic field level can be obtained by reducing the contents of Al and S.

3.2 Evaluation of Magnetic Shielding Effect

Table 2 shows the DC magnetic properties of the test samples. Although the permeability of EFE is reduced somewhat by the effects of temper rolling, its properties are significantly higher than those of steel sheets.

Figure 5 shows the DC magnetic shielding effect, and **Fig. 6** shows the magnetic shielding effect at 50 Hz. With both DC and 50 Hz, EFE shows a superior magnetic shielding effect in comparison with steel sheets. Specifically, the magnetic shielding effect of EFE is 3–6 dB superior to that of steel sheets of the same thickness (0.8 mm), and is generally superior to that of steel sheets with a thickness of 1.2 mm. Thus, these results show that an improved magnetic shielding effect can be obtained with the same sheet thickness by changing the material from steel sheets to EFE due to the higher magnetic properties of the latter. On the other hand, in cases where steel sheets meets magnetic shielding requirements, a satisfactory shielding effect can be obtained using a thinner gauge of EFE, with an accompanying cost reduction effect.

Table 2 Magnetic properties of the test samples

Mark	Thickness (mm)	H_m = 796 A/m				
		B_m (T)	B_r (T)	H_c (A/m)	μm	μ (at 28A/m)
EFE-0.8	0.8	1.48	0.88	99	3 500	640
SPCC-0.8	0.8	0.72	0.50	420	730	140
SPCC-1.2	1.2	1.34	0.99	210	1 900	210

4. Discussion

4.1 Effects of Al and S Contents on DC Magnetic Properties

In order to investigate the cause of the reduction in permeability by trace amounts of Al and S, precipitates were observed using a transmission electron microscope (TEM). The results are shown in **Photo 1**. In material

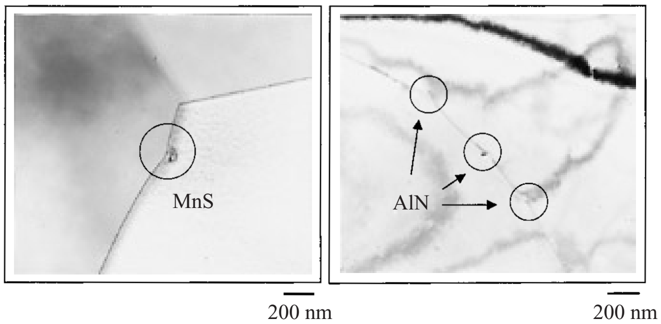

Photo 1 The precipitates on grain boundary

containing Al or S, the grain growth property is reduced by pinning of the grain boundaries by fine precipitates, and magnetic properties are reduced by the resulting fine-grained structure. Accordingly, the most effective means of obtaining good magnetic properties is high purification. Moreover, together with high purification, morphology control of precipitates is also important for achieving high magnetic properties.

4.2 Influence of Permeability and Sheet Thickness on Magnetic Shielding Effect

The magnetic shielding effect is generally evaluated by the product of permeability and the sheet thickness[6]. Where the DC magnetic shielding effect is concerned, **Fig. 7** shows the results when the shielding effect against external magnetic fields with intensities of 8.0−79.6 A/m was arranged using $\mu \times t$. The broken line in the figure shows the results of calculations using an approximation equation[7] expressed by Eq. (2), which considers the shape factor of the shield box.

$$S = 20\log(1 + 0.8\,\mu t/a) \quad \cdots\cdots (2)$$

where, t is the thickness of the specimen material (mm), μ is the specific permeability of the specimen material measured in an excitation field of the same intensity as the external magnetic field during measurement of the

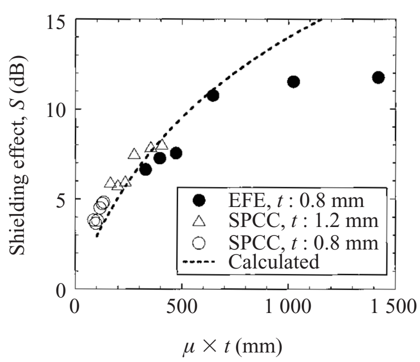

Fig.7 Relationship between the magnetic shielding effect (DC) and $\mu \times t$

shielding effect, and α is the length of one side of the shield box (mm).

Because the shielding effect shows a good correlation with $\mu \times t$ regardless of whether the steel type is EFE or steel sheets or the sheet thickness, the shielding effect is substantially shown by the approximation equation given by Eq. (2). The region where $\mu \times t$ is large contains data which deviate somewhat from Eq. (2). However, because these data are in a region where a large flux is excited in the magnetic body, these deviations are presumed to be due to the large effect of leakage flux in the joints at the corners of the box.

Thus, the results described above revealed that, in order to increase the magnetic shielding effect, it is important to increase permeability at the field intensity where shielding is required, and in comparison with steel sheets, EFE demonstrates a superior shielding effect from low field levels.

5. Conclusion

The effects of trace amounts of impurities on the magnetic properties of a pure iron magnetic shielding material and the magnetic shielding effect when this material was used in a model shield box were investigated. The conclusions obtained were as follows.

(1) In comparison with Al-free steel, Al causes a remarkable reduction in permeability even at contents on the order of 30 ppm. With S, permeability decreases in a basically linear manner as the S content increases in the composition range of 35−180 ppm.

(2) The pure iron magnetic shielding material EFE (0.8mm) possesses a magnetic shielding effect 3−6 dB superior to that of the conventional material steel sheets at the same sheet thickness, and has a magnetic shielding effect equal or superior to that of steel sheets with a thickness of 1.2 mm.

JFE Steel's EFE steel sheet, which is manufactured using a high permeability technology supported by high purification and precipitate morphology control, shows an improved magnetic shielding effect in comparison with steel sheets for general forming applications, and is the optimum material for cost reduction by reducing the sheet thickness of the shield material. Selection of EFE gives expanded design freedom and makes it possible to meet a variety of needs, including higher performance, cost reduction, and weight reduction.

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