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Examination of Magnetic Properties of Several Magnetic Materials at High Temperature

***Abstract**. In order to accurately design magnetic devices which are used at high temperature, it is necessary to understand the behaviour of several magnetic materials at high temperature. In this paper, the magnetic properties of several magnetic materials until Curie temperature are measured. It is shown that the change of iron loss of rolled steel (SPCC and SS400) with the temperature is more remarkable than that of electrical steel sheet.*

***Streszczenie.** W pracy przedstawiono właściwości magnetyczne niektórych materiałów w wysokiej temperaturze. Zmiana strat blachy walcowanej SPCC I SS400 jest znacznie większa niż ma to miejsce w przypadku blach elektrotechnicznych. (**Badania właściwości magnetycznych niektórych materiałów magnetycznych w wysokiej temperaturze**)*

Keywords: high temperature, comparison of magnetic properties, iron loss, specific permeability
Słowa kluczowe: właściwości magnetyczne, straty, wysoka temperature.

Introduction

If the magnetic fields in magnetic devices, which are used at high temperature, are analyzed using the magnetic properties at a room temperature (RM), the obtained results are fairly different from an actual behaviour [1, 2]. In order to accurately design magnetic devices which are used at high temperature, it is necessary to understand the behaviour of several magnetic materials at high temperature. Although the change of magnetization of magnetic material measured using a VSM is well reported [3], the data of magnetic properties, such as *B*-*H* curves and iron loss curves which are indispensable to the precise magnetic field analysis at high temperature are not familiar. We have already reported the measurement method of magnetic properties at high temperature until about 800°C using a ring specimen and discussed the behaviour of the magnetic properties of electrical steel sheets [4]. However, it seems that there is no report about the comparison of magnetic properties of several magnetic materials.

In this paper, the magnetic properties of several magnetic materials up to 700°C are measured using ring specimens. The measured results are compared and some features of each magnetic material at high temperature are discussed.

Method of Measurement

Fig.1 shows the special frame for measuring magnetic properties of ring specimens (outer diameter: 100mm, inner diameter: 70mm, thickness: 0.1-1.0mm) at high temperature. The frame is made of ceramics which can be used until more than 1000°C. The ring specimens are set inside it. The cold rolled steel sheet (SPCC, thickness: 1mm), rolled steel for general structure (SS400, thickness: 0.6mm), 6.5%Si steel (thickness: 0.1mm) and non-oriented electrical steel sheets (35A250, thickness: 0.35mm) are used as specimens. Each sheet of SPCC, SS400, 6.5 % Si steel and 35A250 is set in the ceramic frame. The B coil is wound on the frame. The B coil is a polyester copper wire (PEW) and its diameter is ϕ1.0mm. The exciting coil is wound 80 turns over the B coil and its diameter is 1.5mm. The insulation between coils is kept using a special insulating tape which can be used until about 1000°C. Fig.2 shows the ring sample for the high temperature measurement.

Fig.3 shows the measurement system. In order to measure the magnetic field strength in the specimen, the magnetizing current method was used. The flux density waveform of measured with the B coil is controlled to be sinusoid. The exciting frequency is 50Hz.

Heating Method

A furnace is used for heating. The air inside the furnace is substituted by the nitrogen gas to avoid the oxidation of a specimen. The exciting coil and B coil are connected to outside through the hearth terminals of the lid of furnace. A K type thermocouple was used for the measurement of the temperature.

Air Gap Compensation

Two kinds of setting methods of B coil, one is wound directly on the specimens, and the other is wound on the frame, are examined [4]. It was found that the sectional area of the B coil cannot be determined exactly, if the B coil is wound directly on the specimens. This is, because the insulating tapes are set between each specimens, and also between specimens and B coil. Then, it was decided to wound the B coil on the frame.

The air gap between the B coil and specimen is large, because the B coil is wound on the ceramic frame. As the B coil detects the flux which passes through the air gap together with the flux inside the specimen, the compensation of the flux which passes through air gap is made by subtracting the flux in the air gap. The relationships between the flux density B_{mea} measured by the B coil, the flux density B_{spe} in the specimen, the area of the specimen S_{spe}, the area of air gap S_{air}, the measured magnetic field strength H_{mea}, the flux Φ_{spe} in the specimen, are given by

$$\Phi_{spe} = B_{mea}S_{spe} - \mu_0 H_{mea} S_{air} \tag{1}$$

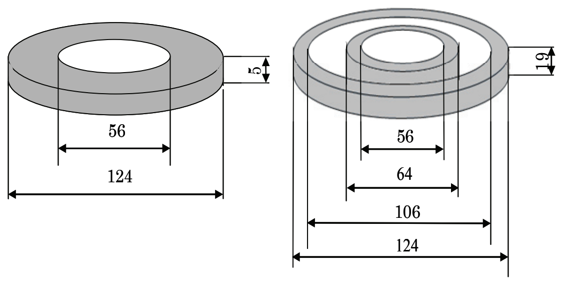
$$B_{spe} = \frac{\Phi_{spe}}{S_{spe}} \tag{2}$$

where μ_0 is the permeability of vacuum. B_{spe} is obtained by (2). The magnetic field strength *H* is calculated from the ampere-turns and the mean magnetic path length. The specific permeability and iron loss are calculated using the obtained B_{spe} and *H*.

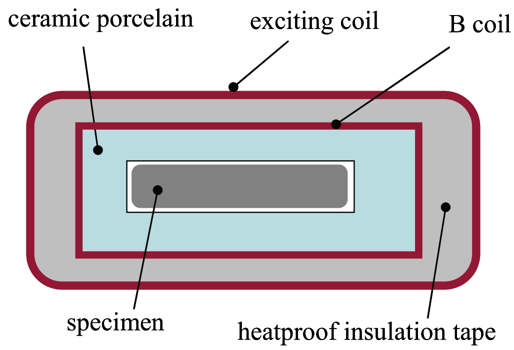
Measured Results and Discussion

Magnetic properties of the ring specimens of the cold rolled steel sheet (SPCC), rolled steel for general structure (SS400), 6.5% Si steel and the non-oriented electrical steel sheet (35A250) are measured up to 700°C.

Figs.4 and 5 show the comparison of *B*-*H* curves and specific permeability μ_s. There are some differences in the change of specific permeability μ_s with increase of temperature. The permeability at low flux density is increased with temperature and that at high flux density is decreased with temperature. The permeability at high temperature (700°C) of SPCC and SS400 becomes maximum at about 0.6T. On the contrary, those of electrical steels (6.5%Si steel, 35A250) become maximum at about 0.3T.



(a) Ceramic frame



(b) Cross section

Fig.1. Special frame for measuring magnetic properties of ring specimens.

Fig.2. Ring sample for measurement at high temperature.

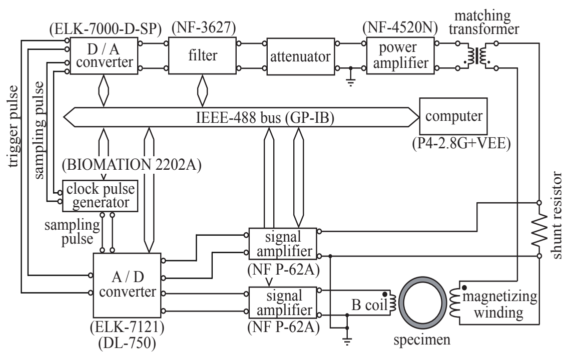
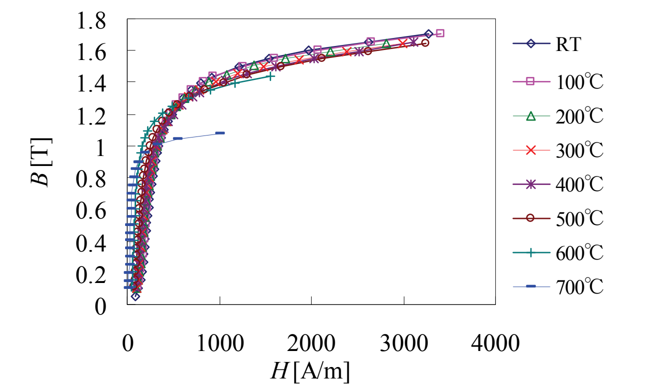
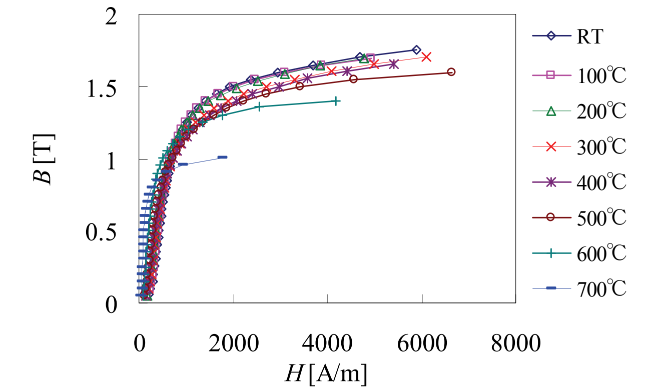


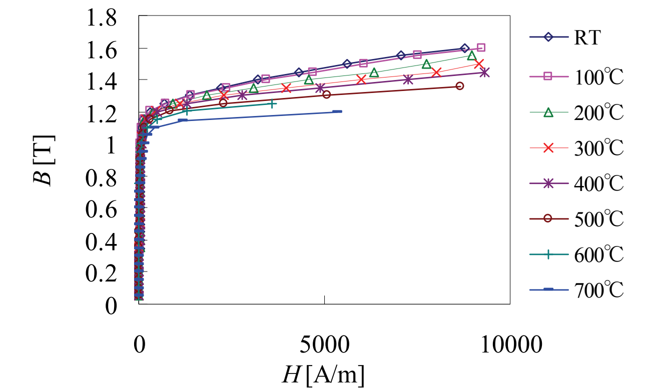
Fig.3. Measurement system.



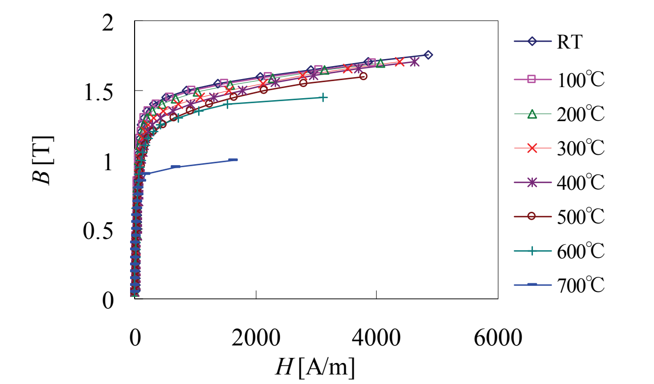
(a) SPCC



(b) SS400



(c) 6.5% Si steel



(d) 35A250

Fig.4. Comparison of *B-H* curves

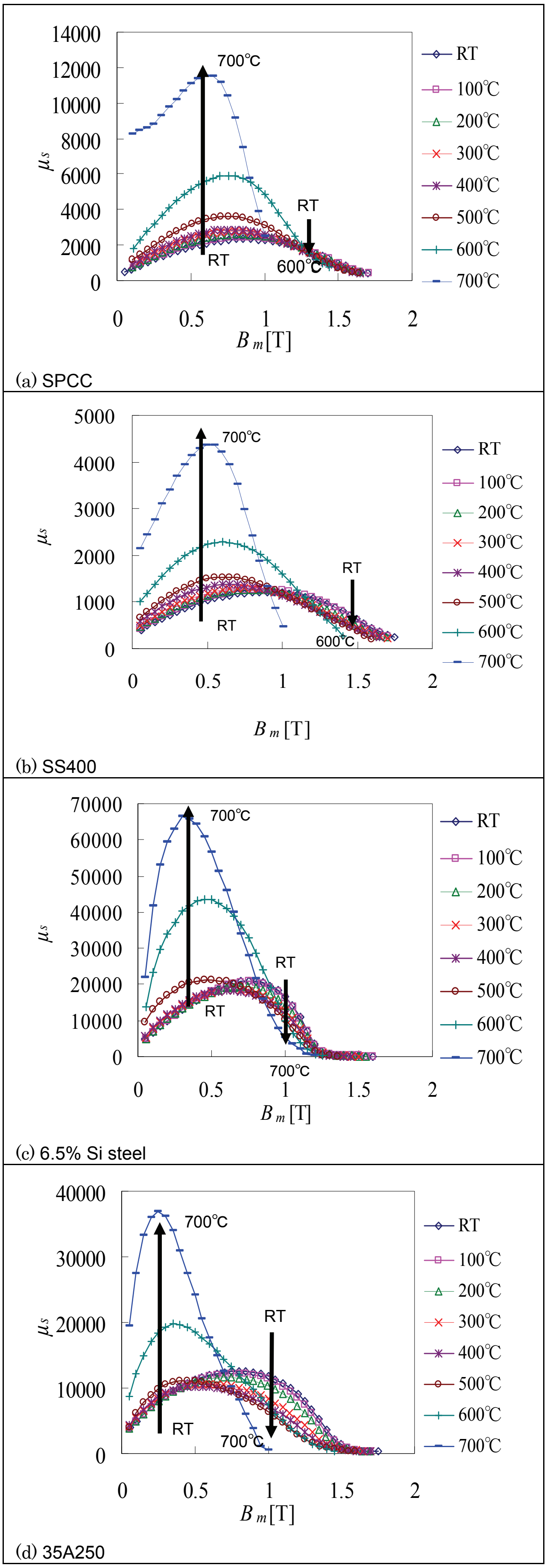


Fig.5. Comparison of permeability μ_s.

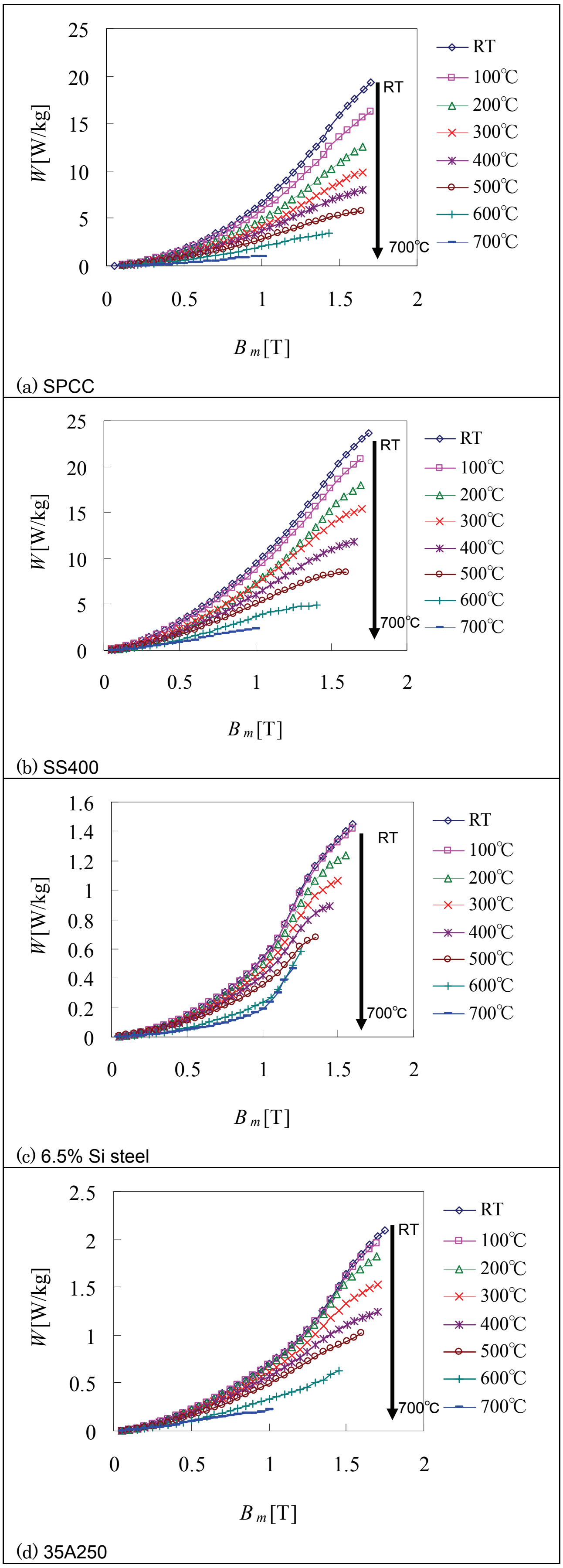


Fig.6. Comparison of iron loss W.

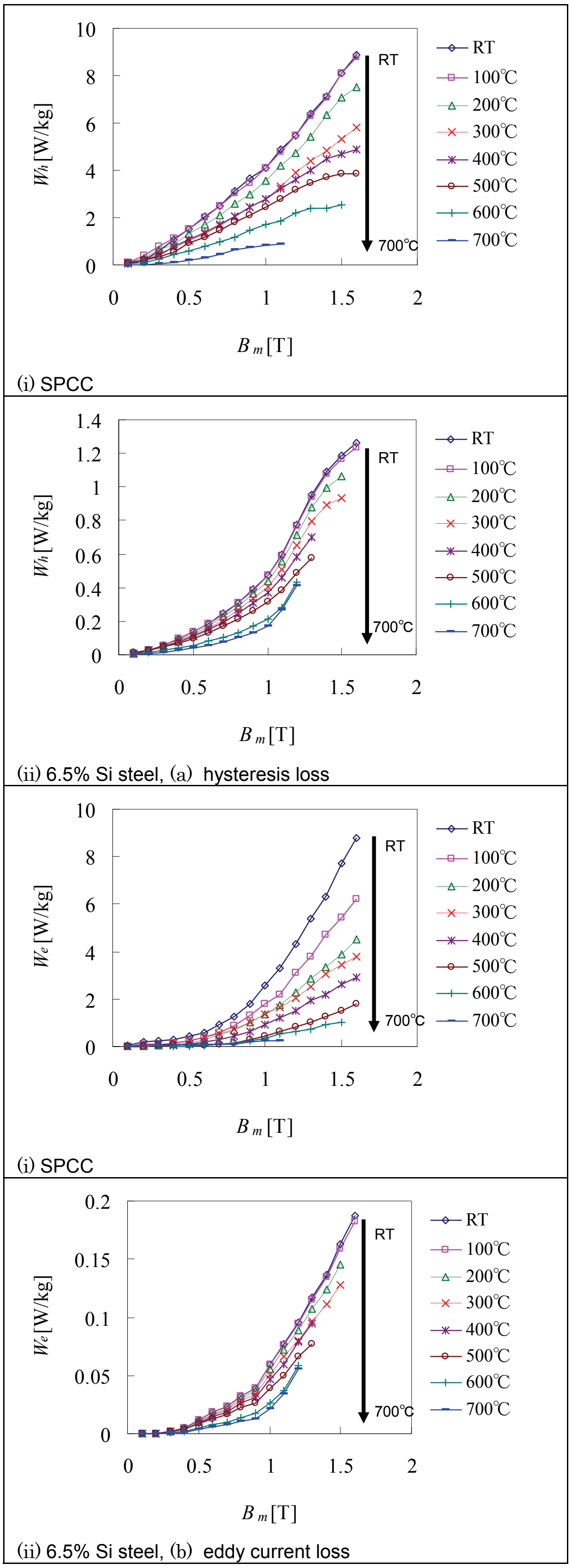


Fig.7. Comparison of hysteresis loss W_h and eddy current loss W_e.

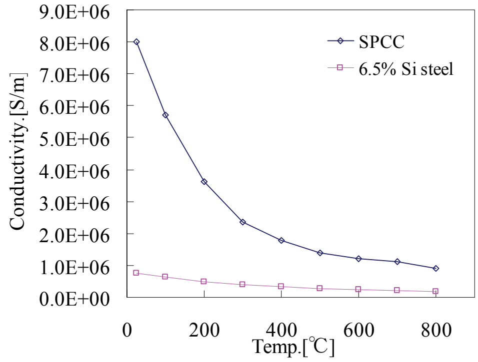


Fig.8. Change of conductivity with temperature.

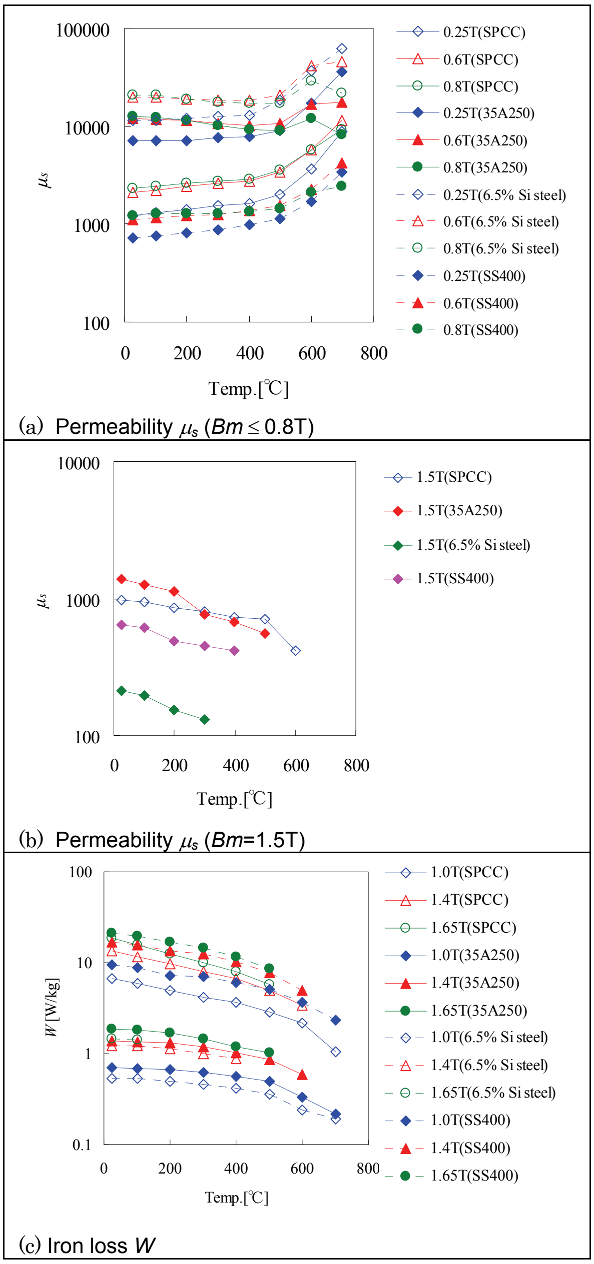
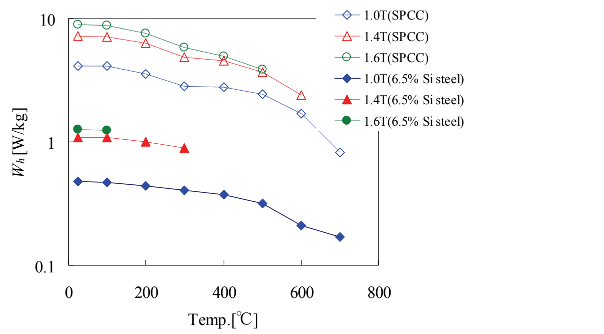


Fig.9. Effect of temperature on specific permeability and iron loss.

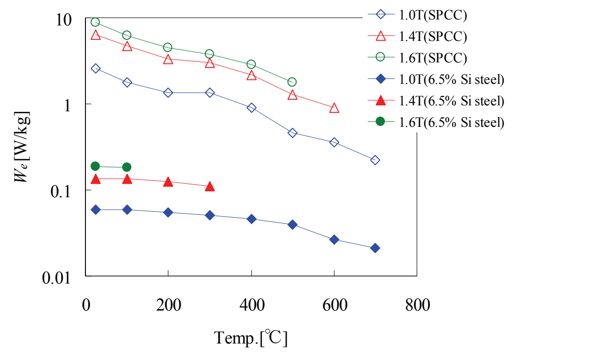
Fig.6 shows the comparison of iron loss W. The iron loss W of all specimens are decreased with temperature. Especially, the decrease of iron loss W with increase of temperature is remarkable in the case of SPCC.

The iron losses W of SPCC and 6.5%Si steel are separated into the hysteresis loss W_h and the eddy current loss W_e by the two-frequency method using iron losses at 30Hz and 50Hz. Fig.7 shows the comparison of the hysteresis loss and the eddy current loss. The hysteresis loss W_h and the eddy current loss W_e of both specimens are decreased with temperature. As the spontaneous magnetization is decreased with the increase of temperature from the weirs theory [5], the area of hysteresis loop is decreased, then it can be considered that the hysteresis loss W_h is reduced with the temperature.

The percentages of eddy current loss to the whole iron loss of SPCC is larger than that of 6.5% Si steel. This is due to the difference in the thicknesses of the specimen. Moreover, the decrease of hysteresis loss W_h and eddy current loss W_e of SPCC with increasing temperature is remarkable in comparison with that of 6.5%Si steel. The remarkable change of W_e of SPCC can be explained by the large change of conductivity (about twice compared with 6.5%Si steel) with the temperature as shown in Fig.8, and the larger eddy current loss compared with 6.5% delete Si steel. The conductivities are measured using rectangular specimens (width: 30mm, length: 100mm) by measuring the voltage difference at two points when dc current is supplied.



(a) Hysteresis loss W_h



(b) Eddy current loss W_e

Fig.10. Effect of temperature on hysteresis loss and eddy current loss**.**

Fig.9 shows the effect of temperature on the specific permeability μ_s and iron loss W. The permeability μ_s at 0.25T is increased with temperature. The tendency similar to the Hopkinson effect[5] is observed. The permeability of SPCC is increased with temperature when the flux density is 0.8T. On the contrary, those of electrical steels (6.5%Si steel and 35A250) don't change so much with the temperature when the flux density is 0.8T.The permeabilities of all the specimens are decreased with temperature at Bm=1.5T as shown in Fig. 9(b). The iron loss is always decreased with temperature as shown in Fig. 9(c).

Fig.10 shows that the hysteresis loss and the eddy current loss are decreased with the temperature and the percentage of eddy current loss to the whole iron loss of SPCC is larger than that of 6.5% delete Si steel.

Conclusions

Magnetic properties of the ring specimens of the cold rolled steel sheet (SPCC), rolled steel for general structure (SS400), 6.5%Si steel and the non-oriented electrical steel sheet (35A250) have been measured and compared. The obtained results can be summarized as follows:

(1)The permeability at high temperature (700°C) of SPCC became the maximum at about 0.6T. On the contrary, those of electrical steels (6.5%Si steel, 35A250) became the maximum at about 0.3T.

(2)The iron losses W of all the specimens were decreased with increasing temperature. Especially, decrease of iron loss W with temperature was remarkable in the case of SPCC.

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