Journal of Magnetics 2(1), 12-15(1997)

Rapidly Solidified Fe-6.5wt% Si Alloy Powders for High Frequency Use

SeungDueg Choi and ChoongJin Yang

Electromegnetic Materials Laboratory, Research Institute of Industrial Science & Technology (RIST), P.O.Box 135, 790-330, Pohang, Korea.

(Received 10 April 1997)

Fe-(3～6.5wt%) Si alloy powders having a high magnetic induction(B_s) and a low core loss value for high frequency use were obtained by an extractive melt spinning as well as a centrifugal atomization technique. Sintered core rings made by the rapidly solidified Fe-6.5wt% Si powders exhibited the high frequency magnetic properties : magnetic induction(B8) of 1.23 T, coercivity(H_c) of 0.12 Oe, relative permeability(μ_a) of 6321, and core loss(W10/50) of 1.27 W/kg from the rings of 1.1 mm thick. The magnetic induction values were found to be almost identical to those of non-oriented Fe-3wt% Si steel sheet and double the value of 6.5wt% Si sheet prepared by the CVD technique. The high frequency core losses(W) up to 10 kHz(W10/10k) were measured to be competitive to those of grain-oriented Fe-3wt% Si steel sheet.

1. Introduction

The rapidly expanding market in audio, video and personal computer has created a similar demand for power supplies, particularly of the switching mode. In the latter, the transformation and filtering are done at high frequency, reducing the volume of the magnetic components by factors of 5～10 and increasing their efficiencies from 35～50% to 75～85%[1]. Recently, the introduction of MOSFET has further extended the operational frequencies(50～100 kHz) of switchers, thus emphasizing the need for magnetic materials amenable to higher frequencies than the original switchers(20 kHz). Among all magnetic materials, ferrites have been the main beneficiary of the increased demand. Their suitability for this application is derived mainly from their very high-frequency operation. In addition, such features as easy formability which has created many new shapes, and their fairly low cost make them more desirable. However, three categories that the ferrite can not satisfy provide the room for metallic components to be used in special requirements[1]. The first category is the component with the high saturation values, secondly the category involving materials which have lower saturation value but, because of their lower losses and availability of very thin gages, can operate at higher frequencies. Thirdly the ability to withstand high dc without a significant drop in permeability is the requirement.

A 6.5wt% Si-Fe has a potential application in magnetic devices due to its high permeability, low hysteresis loss, high electrical resistivity and very low magnetostriction[2～4]. Unfortunately, however, there is practical limit of about 3.5wt% Si above which the materials becomes brittle and difficult to cold-roll. Recently it became possible to obtain 6.5wt% Si sheets by a chemical vapor deposition process consisting of three steps[5]: (1) cold-rolling 3wt% Si steel to the final thickness, (2) heat treating in Si compound vapor and (3) making diffusion from the surface to the center of the sheet.

In this study we report a new technology to produce Fe-6.5wt% Si powders for magnetic cores in high frequency use of power supply. The process involves a melt-extractive rapid solidification of alloy melt into fine size particles directly. The typical magnetic properties are discussed in terms of magnetic induction, core loss as well as permeability as a function of applied frequency.

2. Experimental

The rapidly solidified Fe-(3.5～6.5)wt% Si alloys were prepared in the form of 60 mesh powders using a melt-extractive spinning technique[6] at the substrate speed of 16m/sec. The melt-spun powders were then pulverized into particle sizes of 38~150 μm. Ring shaped cores were made by pressing the powders using a vertical pressure of 8 ton/cm^2 and followed by sintering in a vacuum furnace at 1250~1375 ℃ for 1~4 hours. AC magnetic properties (core loss, permeability) of the core samples were measured at the frequency up to 10 kHz by using a high frequency B-H analyzer (Iwatsu SY-8232), and DC magnetic properties (magnetic induction, coercivity) were characterized by using a B-H curve tracer (Riken Denshi type)

3. Results and Discussion

A. The effect of sintering temperature on magnetic properties

Fig. 1 is a SEM micrograph showing the particle aspect after pulverizing the melt-spun powders for 18 min. Melt spinning at the substrate speed of 16 m/sec gives an uniform thickness of 10~20 μm. Experimentally magnetic induction (B_S) and coercivity(H_c) were measured as a function of sintering temperature of the sample cores in Fig. 2, and core loss(W) and relative permeability(μ=$(1/\mu_0)(B/H)$ are shown in Fig. 3 for Fe-6.5wt% Si alloy sintered for 2 hours. Sintering the cores at a higher temperature enhances the magnetic induction and permeability values as well, and causes low values in the coercivity and core loss. The same trend was also true when the properties were plotted as a function of sintering time. This is because as a higher sintering temperature or longer time is used, the density of cores enhances and coarse grains were formed. It is well known that the larger the grain size, the larger the maximum permeability and the smaller the coercivity. However, since the hysteresis loss tends to be smaller and the eddy current loss tend to be larger, it is desirable to find an optimum grain size. In this study the optimized sintering temperature was found to be 1375 ℃ for Fe-(3.5~6.5)wt% Si powders.

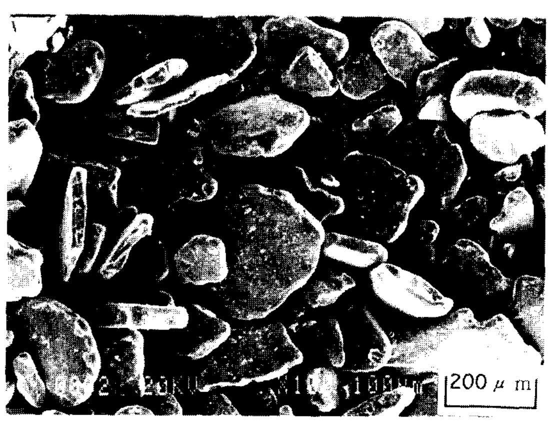

Fig. 1 SEM micrograph showing the pulverized Fe-6.5wt% Si powders made by the extractive melt spinning process

B. The effect of Si content on the magnetic properties

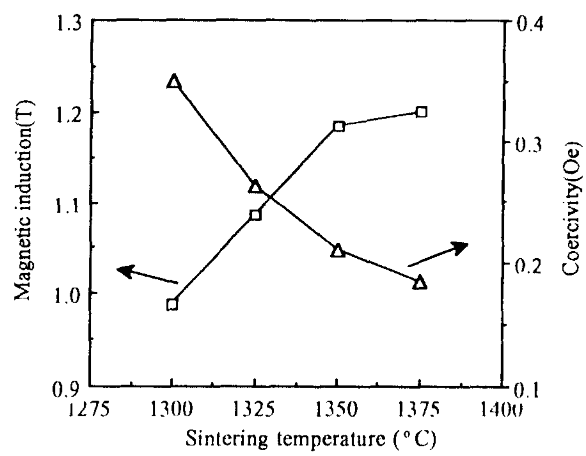

Fig. 2 Variation of magnetic properties of Fe-6.5wt% Si alloy as a function of sintering temperature (sintering time : 1 hr, applied field : 10 Oe)

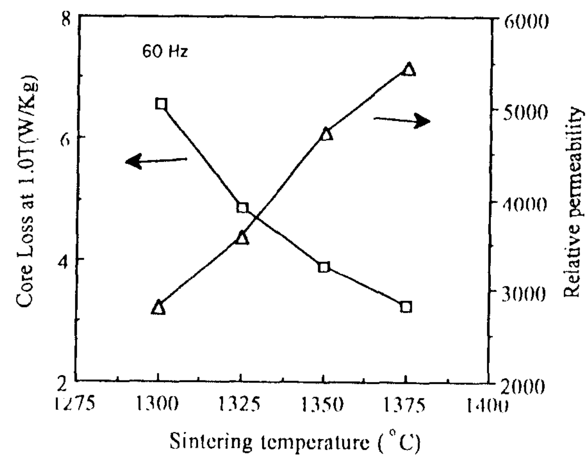

Fig. 3 Core loss and relative permeability of Fe-6.5wt% Si alloy as a function of sintering temperature. (time : 2 hrs)

Both the magnetic induction and coercivity were found to decrease monotonically as Si content increases from 3.5 to 6.5wt%. The figure of merit for this high Si-Fe alloy is to obtain the magnetic induction as high as possible and a high permeability as well. But with increasing Si content up to 6.5wt% the magnetic induction tends to decrease while the permeability increases. Fig. 4 shows the variation of permeability measured at 60 Hz against the magnetic field produced by the second coil. The core samples were sintered at 1350 ℃ for 1 hour. The permeability was obtained to decrease slowly as the applied magnetic field increase. Anyway, the permeability values measured from the samples of a higher Si content always show a higher value. Fig. 5 shows the variation of core loss measured against the magnetic field produced during measuring the same samples sintered at 1350 ℃ for 1 hour. The core loss plotted in semi-log scale increases linearly against the magnetic induction of the core samples. However, the alloy of a higher Si content

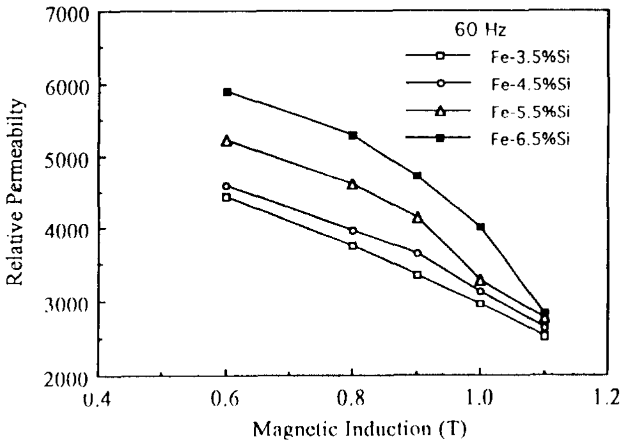

Fig. 4 Relative Permeability of Fe-(3.5~6.5)wt% Si alloys sintered at 1350 ℃ for 1 hr.

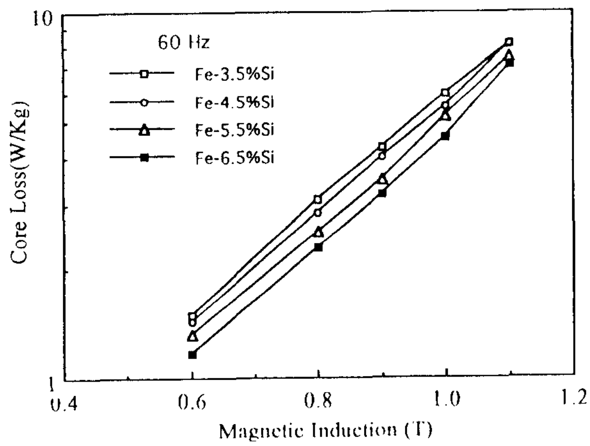

Fig. 5 Core loss of Fe-(3.5~6.5)wt% Si alloys sintered at 1350 ℃ for 1 hr.

exhibits a lower loss. The core loss of 0.5~9.0 W/kg at 60 Hz with a magnetic induction ranging from 0.6 to 1.0 Tesla is a quite low value compared with a conventional 3wt% Si alloy. The core loss of 6.5wt% Si is known to be almost half the conventional ones at 400 Hz~10 kHz[7]. This is because the core loss may be expressed in the form of:

$$W = \text{cont.}B^m f^n$$

where m is about 1~2 at high frequency(f), and n lies between 2 and 3 being dependent upon the materials concerned. The empirical exponents for m=2.05 and n=1.5 are generally accepted for metallic powder cores[8]. In Fig. 6 the variation of core loss can be seen that the trend follows in second power proportion to frequency which is more prominent for the alloy of low Si content. If one consider the effect of grain size on the core loss, the loss can be expressed in the form of:

$$W \propto \text{const.}\,(B \cdot f \cdot d)^2$$

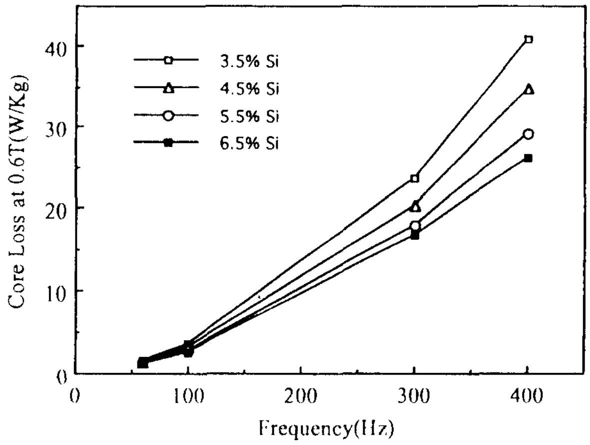

Fig. 6 Core loss of Fe-(3.5~6.5)wt% Si alloys sintered at 1350 ℃ for 1 hr as a function of frequency.

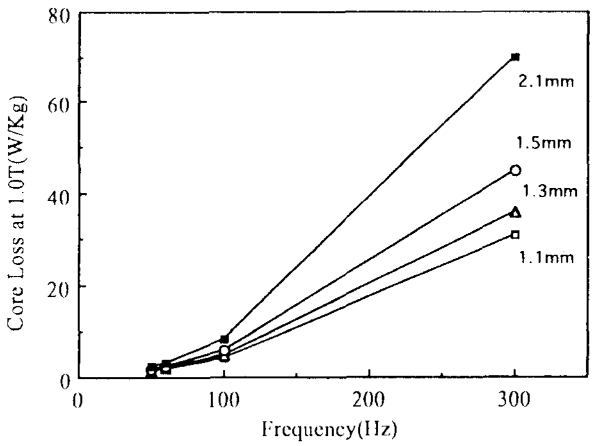

Fig. 7 Core loss of Fe-6.5wt% Si alloy sintered at 1375 ℃ for 2 hrs as a function of frequency at various thickness.

where d denotes the grain size or thickness of the sample to be measured. Fig. 7 shows the variation of core loss of the same samples to those of Fig. 5 and 6 against the frequency used. As the thickness of core sample increases, the curve tends to follow a second power proportion to the thickness. In Table I the typical magnetic properties obtained at high frequencies are summarized.

Table I. Comparisons of magnetic properties between conventional Fe-3wt% Si sheet and sintered Fe-6.5wt% Si powders(RIST's)

product	thickness (mm)	Bs (Tesla)	core loss (W/kg)			
			$W_{10/50}$	$W_{10/400}$	$W_{10/1k}$	$W_{10/10k}$
Grain-oriented Fe-3wt% Si	0.35	1.93	0.9	12.3	15.2	50
Non-oriented Fe-3wt% Si	0.35	1.42	1.3	17	20	55
sintered Fe-6.5wt% Si	1.10	1.23	1.27	20	20	50

4. Conclusion

Switching mode power supply(SMPS) is expected to be used at higher frequency than ever and with non-sinusoidal drive. A Fe-6.5wt% Si alloy satisfies these needs and has demonstrated its characteristics in this field. A cost-effective melt-spinning process can be applied for producing the Fe-6.5wt% Si powders with a high magnetic induction(B_s=1.23 Tesla) and a high relative permeability(μ_a=6321), and a low coercivity(H_c=0.12 Oe). Core loss($W_{10/50}$) of 1.27 W/kg at low frequency range implies a potential use of this powder type cores for high frequency SMPS.

References

[1] A.Goldman, in Advances in Ceramic, Vol.16, 4th Inter. Conf. on Ferrites Part II, ed. by F.Y. Wang (The American Ceramic Society, Inc., Columbus, OH, 1995), p. 421

[2] Y.Takada, J. Appl. Phys., **64**(10), 5367(1988)

[3] M.Abe, J. Mater. Eng., **11**(1), 109(1989)

[4] Y.Takada, J. Magn. Magn. Mater., **83**, 375(1990)

[5] Y.Takada, A.Miura and S.Masuda, NKK Technical Rev., **60**, 9(1990)

[6] C.J.Yang and R.Ray, J Metal Powder Report, **43**, 54(1989)

[7] E.C.Snelling, Soft Ferrite:Properties and Applications (Butterworth, London, (1938), p. 35

[8] Catalog, Kool Mu Powder Cores, Magnetics Corp., Butler, PA, (1991)