Research Article

Magnetic Properties and Core Loss Behavior of Fe-6.5wt.%Si Ribbons Prepared by Melt Spinning

S. Wang, Y. M. Jiang, Y. F. Liang, F. Ye, and J. P. Lin

State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, China

Correspondence should be addressed to Y. F. Liang; liangyf@skl.ustb.edu.cn

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Fe-6.5wt.%Si alloy is prepared in the form of continuous ribbons with 25 mm in width and 0.03 mm in thickness by using melt spinning technique. The ribbons are flexible and could be wound into tapes. DC magnetic properties and core loss behaviors of the ribbons after heat treatment are investigated in this paper. The magnetic properties are compared with ribbons by cold rolling and CVD methods. The melt spinning ribbons exhibit much less core loss in the frequencies more than 10 kHz. The melt spinning ribbons are promising to be used for electric devices used in medium or higher frequencies.

1. Introduction

High silicon steels (Si content $\geq 4.5\text{wt.}\%$) have been considered as potential materials for application in distribution transformers owing to their excellent soft magnetic properties [1]. Particularly high silicon steel containing 6.5wt.%Si has potential applications in magnetic devices due to its high permeability, high magnetization, high Curie temperature, and very low magnetostriction, as well as low core loss. However, it has not been used widely because of its poor mechanical workability at room temperature. The fabrication of Fe-6.5wt.%Si ribbons through conventional rolling process is difficult owing to inherent brittleness of the material [2]. The brittleness is due to the formation of ordered phases and coarse grains [3, 4]. It can be overcome by the rapid solidification technique like melt spinning. Enokizono et al. successfully prepared Fe-6.5wt.%Si ribbons with 0.01–0.04 mm in thickness and about 1–2 mm in width [5].

In the present work, we obtained ribbons with 0.03 mm in thickness and 25 mm in width prepared by melt spinning technique. Magnetic properties and core loss behaviors are studied in this paper.

2. Experiments

Fe-6.5wt.%Si master alloy was prepared by melting iron and metallic silicon (99.5% purity) in a vacuum induction furnace

and then poured into an ingot mold. Table 1 shows the chemical analysis of the alloy.

The Fe-6.5wt.%Si ribbons were prepared by melt spinning technique. A melt spinning equipment mainly includes medium-frequency induction furnace, nozzle, and copper roller cooled by water. In the process of preparing ribbons, the alloy of Fe-6.5wt.%Si was put in the medium-frequency induction furnace and was melted. A stream of the molten alloy was ejected onto the surface of the copper roller through the nozzle by adding a constant pressure in the furnace. The molten alloy was then quenched rapidly by the copper roller and formed into a long ribbon.

By optimizing the size of the nozzle, the ejection pressure, the temperature of the molten alloy, the space between nozzle and copper roller, and the speed of rotation roller, the ribbons were successfully prepared in the form of 20 mm in width and 0.03 mm in thickness and could be wound into tapes, as showed in Figure 1. Surface quality of the ribbon is good and the two edges of the ribbon are straight. These ribbons are flexible and could be bent into 180° without crack.

For measurement of the magnetic properties, the ribbons were cut into 10 mm wide, coated by MgO powders, and wound into toroidal core. The inner and the outer diameter of the core were 15 mm and 23 mm, respectively, as shown in Figure 2.

FIGURE 1: Fe-6.5wt.%Si ribbons with 25 mm in width and 0.03 mm in thickness prepared by melt spinning.

FIGURE 2: Wounded toroidal cores by Fe-6.5wt.%Si ribbons, before (left) and after (right) winding copper wires for magnetic testing.

TABLE 1: Chemical composition of Fe-6.5wt.%Si alloy.

Element	Si	C	Mn	P	S	B	Fe
wt.%	6.46	0.0034	0.04	0.0056	0.0013	0.0005	The rest

It is reported that the soft magnetic properties of the ribbons are degraded by stresses produced during the production process [6], while B2 and D0₃ order phases are suppressed [7]. The ordered phases are helpful to improve magnetic properties [8]. So the core should be annealed for improving magnetic properties. In this work, the toroidal core was annealed at 1100°C for 5 hours in vacuum and then cooled in furnace to room temperature. For measurement, the annealed cores were put in nylon case to avoid further stress and then primary and secondary copper wires were wound, as shown in Figure 2.

The structure of the ribbons before and after heat treatment was studied using X-ray diffractometry (XRD, Rigaku, Ultima IV) and transmission electron microscopy (TEM, FEI Tecnai F30). The AC and DC magnetic properties of the cores were measured using NIM-2000S AC instrument and NIM-3000S DC instrument, respectively. The AC and DC magnetic

FIGURE 3: XRD patterns of melt-spun specimens before and after heat treatment (1100°C/5 h + FC).

properties are compared with the magnetic properties of ribbons produced by cold rolling and CVD methods.

3. Results and Discussion

3.1. Microstructural Characteristics. Figure 3 presents the XRD results of melt-spun specimens before and after heat treatment. B2 reflection is not observed in as-spun specimens, while a weak B2 reflection can be observed after heat treatment.

The phase evolution can be also confirmed from the TEM diffraction patterns in Figures 4 and 5 with bright-field TEM micrograph and the corresponding SADP. It is found that there is no B2 phase in as-spun specimens as shown in Figure 4, while the appearance of B2 phase is obvious after heat treatment as shown in Figure 5.

3.2. DC Magnetic Properties. DC magnetic properties of the ribbons after heat treatment were measured in static magnetic field, as shown in Table 2 compared with the ribbons prepared by cold rolling and CVD methods. B_8 , B_{25} , and B_{50} are maximum magnetic flux density measured at the DC magnetic field of 800 A/m, 2500 A/m, and 5000 A/m, respectively.

The values of B_8 and B_{25} are very close between melt-spun ribbons and CVD ribbons. The relative permeability (μ_r) of the melt-spun ribbon is only about half of CVD ribbon. The reason is mainly due to the ultrathin thickness of the melt-spun ribbons. Coercivity of the melt-spun ribbon is as good as cold-rolled one. The DC hysteresis loop was measured at a magnetic field up to $H = 10000$ A/m, which is shown in Figure 6.

3.3. AC Magnetic Properties. Table 3 shows the core losses of melt-spun ribbons compared with ribbons from cold rolling and CVD methods. It is found that melt-spun ribbons exhibit less core losses than cold-rolled and CVD ones.

FIGURE 4: TEM micrographs of the as-spun Fe-6.5wt.%Si ribbons. (a) Bright-field image; (b) SADP of the zone axis of [001]; (c) the corresponding schematic illustration, where only A2 phase is identified.

TABLE 2: DC magnetic properties of ribbons produced by melt spinning.

	Thickness (mm)	Magnetic flux density (T)			Residual magnetic flux density (T)	Relative permeability	Coercivity (A/m)
		B_8	B_{25}	B_{50}	B_r	μ_r	H_c
Melt spinning ribbon	0.03	1.27	1.38	1.50	1.12	11234	35.65
Cold rolling ribbon [9]	0.05	1.40	—	—	—	11200	40.83
CVD ribbon [4]	0.1	1.29	1.40	—	—	23000	—

TABLE 3: Core losses of melt spun ribbons compared with ribbons from cold rolling and CVD.

Method	Thickness (mm)	Core loss (W/kg)									
		$P_{1/400}$	$P_{0.5/1\text{ K}}$	$P_{0.1/5\text{ K}}$	$P_{0.2/5\text{ K}}$	$P_{0.05/10\text{ K}}$	$P_{0.1/10\text{ K}}$	$P_{0.05/20\text{ K}}$	$P_{0.07/20\text{ K}}$	$P_{0.07/30\text{ K}}$	$P_{0.07/40\text{ K}}$
Melt spun	0.03	7.31	5.47	1.90	6.99	1.21	4.62	3.13	6.03	10.86	16.69
Cold rolled	0.05	8.66	6.3	—	8.82	—	6.23	—	8.81	16.5	26.1
CVD	0.05	6.1	4.6	—	6.2	—	5.1	—	7.0	12.7	20.5

FIGURE 8: Variation of maximum permeability μ_r with frequency.

The eddy current loss P_e can be explained by simple “classical” model [11, 12] using Maxwell’s electrodynamics, which is given by

$$P_e = \frac{\pi^2 d^2 B_m^2 f^2}{\beta \rho}, \quad (3)$$

where d is the thickness of the magnetic material ribbon, f is the frequency, ρ is the resistivity, and β is the geometric factor.

There is great progress in measurement of excess loss using the statistical loss models [13–15], where magnetization dynamics were explained by statistics of a group of interacting domain walls, termed as magnetic objects (MO). Excess loss (P_{exc}) can be given by

$$P_{exc} = k_{exc} B^{3/2} f^{3/2}. \quad (4)$$

Using all these models, namely, Steinmetz hysteresis model, classical eddy current loss mode, and statistical excess loss model, the total core loss can be written as

$$P_t = k_h B^n f + k_e B^2 f^2 + k_{exc} B^{3/2} f^{3/2}, \quad (5)$$

where k_h , k_e , and k_{exc} are, respectively, hysteresis, eddy current, and excess loss coefficient.

To identify the values of the coefficients, (5) is divided by the frequency resulting in

$$P_{cy} = \frac{P_t}{f} = k_h B^n + k_e B^2 f + k_{exc} B^{3/2} f^{1/2}, \quad (6)$$

where P_{cy} is the power loss per cycle. Equation (6) shows that hysteresis power loss per cycle does not depend on frequency. In this paper, the loss coefficients (k_h , k_e , and k_{exc}) and exponent of B (“ n ”) have been determined by fitting of (6) within frequencies from 400 Hz to 40 kHz.

The k_h and “ n ” were determined by least square fitting, which is shown in Figure 9. The exponent “ n ” value is 1.78 and k_h value is 115.7. To further determine k_e and k_{exc} , the “ n ” and k_h are put into (6). The modified (6) is written as

$$P_{cy} = 115.7 B^{1.78} + k_e B^2 f + k_{exc} B^{3/2} f^{1/2}. \quad (7)$$

FIGURE 9: Variation of loss per cycle with B at DC magnetic field.

Equation (7) is then fitted with P_{cy} -frequency curves at constant B . The obtained k_e and k_{exc} are plotted in Figure 10. It is found that the value of k_e and k_{exc} depend on the value of B , the value of k_e is between 0.002 and 0.0043, and the value of k_{exc} increases with increasing B value, leading to larger excess core losses at larger B values, as shown in Figure 11.

The k_h , k_e , k_{exc} , and “ n ” are put into (6) and then proportions of hysteresis loss (P_{hys}), eddy current loss (P_e), and excess loss (P_{exc}) can be calculated at different conditions. Based on this result, people can adjust the production process and optimize heat treatment parameters to decrease the core loss.

4. Conclusions

- (1) Fe-6.5wt.%Si ribbons are prepared by melt spinning technique. Compared with cold rolled and CVD ribbons, the melt spinned ribbons possess much lower core losses at medium and high frequencies.
- (2) Magnetic properties of the as-spinned ribbons are improved after heat treatment of 1100°C/5 h with furnace cooling. Phase transformation of A2 to B2 is obvious after heat treatment.
- (3) The loss coefficients are dependent on the flux density and the frequency. The value of k_e is between 0.002 and 0.0043, and k_{exc} increases with B value, leading to larger excess core losses at larger B values.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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FIGURE 10: Variation of eddy current and excess loss coefficients (k_e and k_{exc}) with flux density B .

FIGURE 11: Variation of loss per cycle (P_{cy}) with frequency at different B values.

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