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Article

AC iron loss prediction and magnetic properties of Fe–6.5 wt.%Si ribbons prepared by melt-spinning

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Abstract: Ultra-thin Fe–6.5wt.%Si ribbons with 35 μm in thickness were prepared by melt-spinning. The magnetic properties were investigated before and after annealing 1000 ºC. DC properties and low-frequency (400 Hz ~ 10 kHz) iron losses have significantly improved after heat treatment. A simplified formula based on Steinmetz law which can be used to predict the AC iron loss is presented. According to the results of some iron losses data, a simplified formula has been determined, and the extent of AC iron losses can be predicted. The results obtained from the formula predict AC iron loss to a good degree. The method developed in this work could be extended to other magnetic materials for predicting AC iron loss with greater ease.

Keywords: Fe–6.5 wt.% Si; Ribbon; Melt spinning; AC iron loss prediction; Magnetic properties

1. Introduction

Silicon steels are mainly used in transformers, power generators and motors as important soft magnetic materials. In these, core loss occurs due to hysteresis and eddy current circulation during usage, wherein the hysteresis loss is linear to frequency, and the eddy current loss is proportional to the square of the frequency. Therefore, eddy current loss accounts for a large proportion in high frequency use.

Compared with the ordinary silicon steel, Fe-6.5wt.%Si (high silicon steel) alloy has many advantages in magnetic properties, such as its properties of near zero magnetostriction, high permeability, high resistivity, low noise and low core loss[1]. The high resistivity aids in the suppression eddy current and thus leads to a significant reduction in eddy current loss.

However, due to the brittleness of Fe-6.5wt%Si originated from ordered phases of B2 and $D0_3$ [2,3], it is extremely difficult to produce the Fe-6.5wt%Si alloy by traditional hot-cold rolling process. Rapid solidification can suppress the transformation of ordered phases due to great cooling rate, and thereby enhance the ductility [4]. Melt-spinning can be used for refining grains [5] and preparing magnetic material ribbons with good magnetic properties [6]. Previously, high-silicon steel ribbons of 25 mm width were prepared by melt-spinning [7]. In this paper, various heat treatments were applied to the as-spun Fe–6.5 wt.% Si ribbons. The relationship between microstructures and magnetic properties was investigated. In addition, a method based on Steinmetz law for prediction of iron loss is presented and verified.

2. Materials and Methods

Herein, Fe–6.5wt.%Si ribbons with 35 μm thickness were used. The composition of the ribbons measured by chemical analysis was Fe: 93.54 wt.%, Si: 6.46 wt.%. Micromorphology and cross-sections of the ribbons were observed using the SEM.

For magnetic properties measurement, the Fe–6.5wt.%Si ribbons were cut into 10 mm wide and subsequently coated with MgO powders which plays the dual roles of insulation and adhesion prevention. Moreover, the ribbons were wound into a toroidal core of 32 mm inner and 40 mm inner and outer diameter respectively (Figure 1 inset). The alternating current (AC) and direct current

(DC) magnetic properties were measured using the NIM-2000S AC and NIM-3000S DC instruments respectively. B_8, B_{50} were tested at magnetic field strength of 800 A/m, 5000 A/m respectively.

To explore the changes in magnetic properties with greater accuracy and reduce the number of errors caused by differences between the different samples, the same core was tested over five rounds of measurement. It should be noted that first the core was tested without heat treatment and subsequently it was annealed in an Ar atmosphere at 1000 ℃ for 0.5 hour (referred to as 0.5 h), following which the magnetic properties were tested. Subsequently, the same core was heated in an Ar atmosphere at 1000 ℃ for plus 1 hour (referred to as 1.5 h), then 1000 ℃ for plus 1.5 hours (referred to as 3 h) and then plus 2 hours (referred to as 5 h). After each heat treatment, magnetic properties were tested, as well as the grain sizes to be observed.

3. Results and Discussion

The DC properties of Fe-6.5wt.%Si ribbons are shown in Table 1, and it is evident that theDC properties has been greatly improved after the 1000 ℃ heat treatment, which is reflected in the improvement of the magnetic permeability, B_8 and reduction in coercivity value.. It is observed that there is almost no change in B_{50} before and after heat treatment, owing to the sufficiently large magnitude of the external magnetic field, resulting in the same value of the magnetic induction due to an identical arrangement of the magnetic domain.

Table 1. DC properties of Fe-6.5wt.%Si ribbons.

sample	μ_m	B (T)		Hc (A/m)
		B8	B50	
0 h	1,843	1.16	1.55	237.6
0.5 h	10,589	1.31	1.55	48.9
1.5 h	10,931	1.31	1.55	46.6
3 h	11,082	1.31	1.55	45.7
5 h	11,051	1.32	1.56	45.3

Figure 1 presents the values of AC iron losses. The iron loss corresponding to the frequency range between 400 Hz and 10 kHz shows a decreasing trend with heat treatment at 1000 ºC. For frequencies higher than 10 kHz, the iron loss increases compared to the as-spun state. Figure 2 (a) ~ (e) show the free surfaces of the ribbons and Figure 2 (f) depicts the grain sizes on the free surface with respect to the annealing time. Figure 2 (a) and (b) insets represent the longitudinal sections of the ribbons before and after heat treatment. The original ribbons consist of equiaxed grains on the wheel surface (the surface contacting the copper roller) and columnar grains on the free surface (the surface not contacting the roller). The grain size is small and uniform. After subjecting to 1000 ℃ for 0.5 hour, each grain extents through the entire thickness, and the grain size increases from a few microns to about 30 microns. With increasing the heat treatment time, the grain size tends to increase but very slowly. The ribbon surfaces would hinder the growth of grain size [8]. After heat treatment, the grain growth results in reduction of grain boundaries, which aids in the reduction of the obstacles of the movement of magnetic domains, thereby reducing the hysteresis loss.

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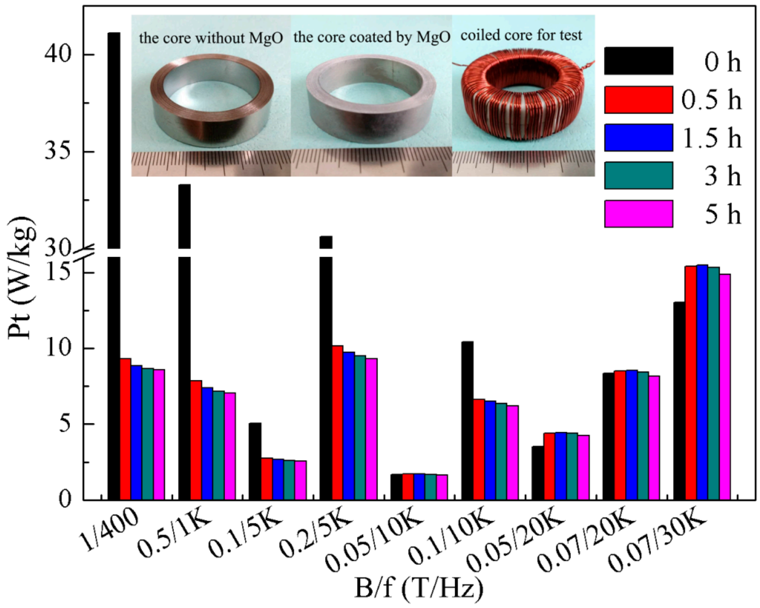

Figure 1. Iron losses corresponding to different conditions before after heat treatment; the inset represent the samples for test.

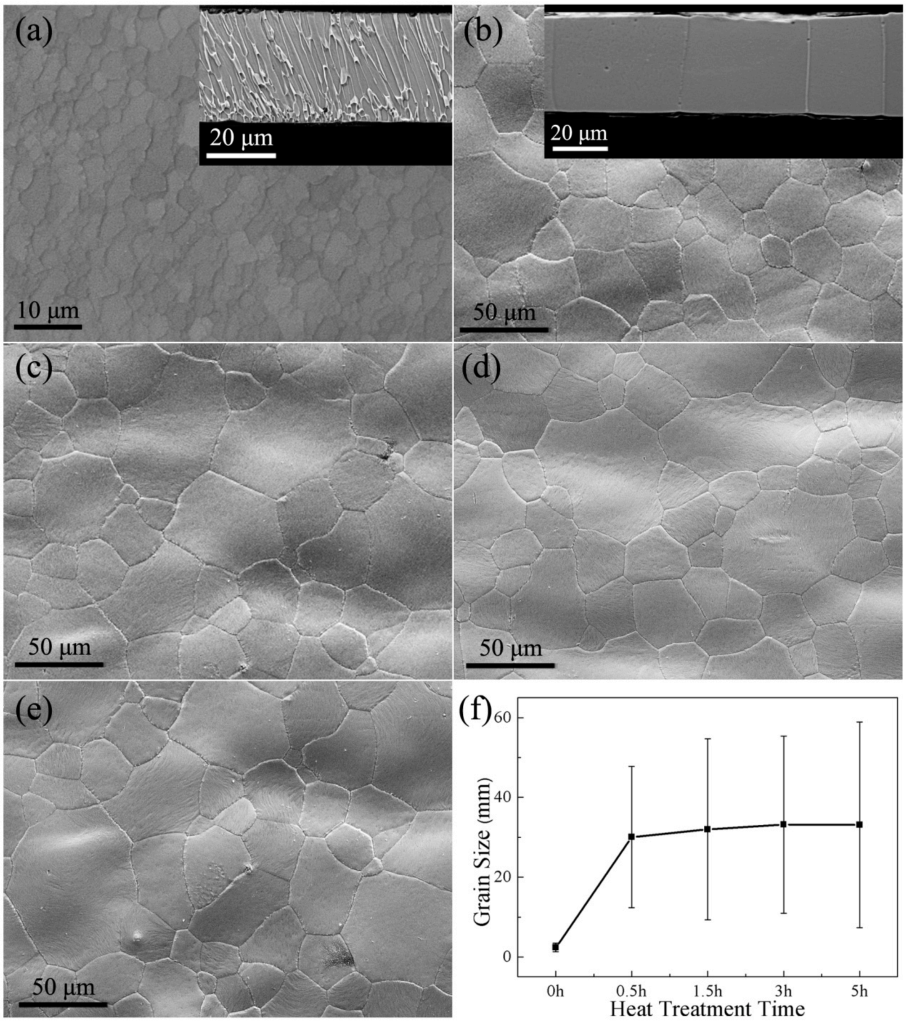

Figure 2. Free surface microstructure of Fe-6.5wt.%Si ribbons (a) in absence of heat treatment; (b) of 1000℃, 0.5 h; (c) 1000 ℃, 1.5 h; (d) 1000 ℃, 3 h; (e) 1000 ℃, 5 h. (f) Grain size statistics.

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Figure 3 depicts the results of the hysteresis loss curves and the AC iron loss curves. It is well known that the Steinmetz law [9] is used to describe the relationship between P_{hys} (hysteresis loss) and B_m (maximum magnetic induction), wherein: $P_{hys} = k_h B_m^n$ at DC field, where, k_h is the hysteresis loss coefficient, and n is the exponent of B_m, which is always near 1.6. The different color formulas in the Figure 3 (a) represent the fitting results of DC iron loss for different heat treatment time. R^2 is the goodness of fit and the closer the value is to 1, the better the fit is. From Figure 3 (a), the DC iron losses decrease drastically after heat treatment and trends to decrease with extension of duration of heat treatment and the coefficients of the fitted results ("k_h" values) also have such a tendency. Generally, the "k_h" value is affected by the kind of material, thickness, stress, grain size, etc. Any factor that reduces the resistance of magnetic domain motion can reduce the "k_h" value.

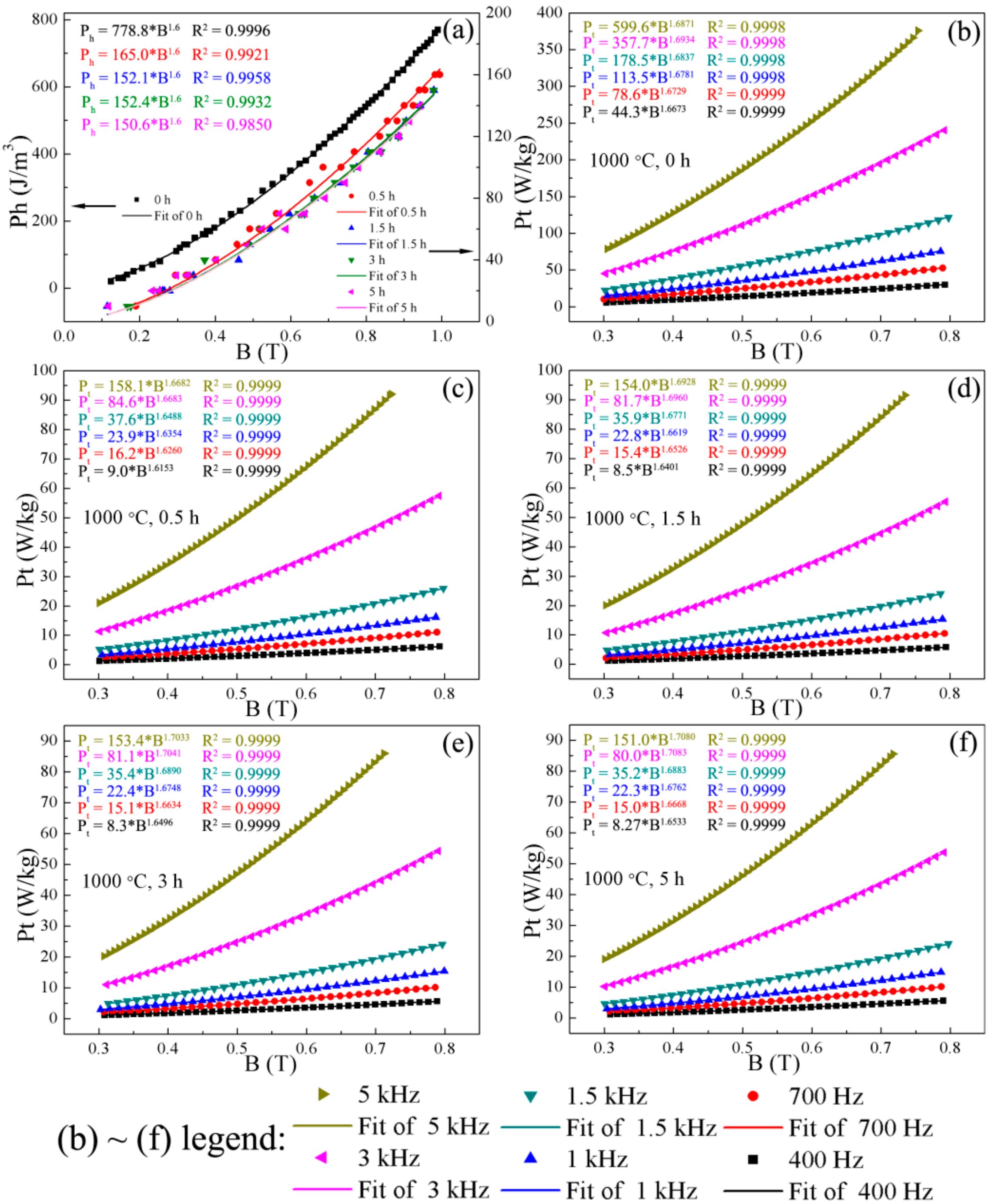

Figure 3. AC and DC iron losses and fit results before and after heat treatment, (a) DC iron losses - magnetic induction curves; (b) ~ (f) AC iron losses - magnetic induction curves at different frequencies. R2 is the goodness of fit wherein, the closer the value is to 1, the better the fit is.

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Ever since Steinmetz formulated the law, many modifications have been proposed, such as the "AC Steinmetz law": $P_t = k_{ac}B_m^n f^\alpha$, where f is the AC frequency [10,11]. And upon comparing hysteresis loss curve and AC iron loss curve from Figure 3, it can be seen that their shapes are similar, exhibiting as monotonically increasing concave functions. Here, we simplify the AC Steinmetz law into $P_t = k_t B_m^N$ similar to "Steinmetz law" $P_{hys} = k_h B_m^n$ and different to "AC Steinmetz law" $P_t = k_{ac}B_m^n f^\alpha$ wherein "k_h" is defined as a function of microstructure and frequency. The simplified formula is used to fit the AC iron loss data in this paper. According to the tested results of iron loss, the values of "k_h" and "N" can be fitted, as shown in Figure 3 (b) ~ (f). The different color formulas represent the fitting results of different frequencies. The prediction of iron loss through the formula - $P_t = k_t B_m^N$ is based on determining of "k_h" and "N".

Figure 4 (a) and (b) depict the results of "k_h" and "N". The different color formulas represent the "k_h" and "N" fitting results of different frequencies. Based on this fitting results, we can calculate the values of "k_h" and "N" at other frequencies. And then, "k_h" and "N" are taken into AC iron loss formula to predict the iron loss at other frequencies, such as 1.3 kHz, 4 kHz. From the Figure 4 (a) and (b) fitting results, "k_h" and "N" can be gained at 1.3 kHz, 4 kHz and core losses prediction results are shown in the Figure 4 (c) and (d). In order to verify the accuracy of the prediction, iron losses were tested and compared at 1.3 kHz and 4 kHz. From Figure 4 (c) and (d), the calculated value was found to be in a good agreement with the actual test results.

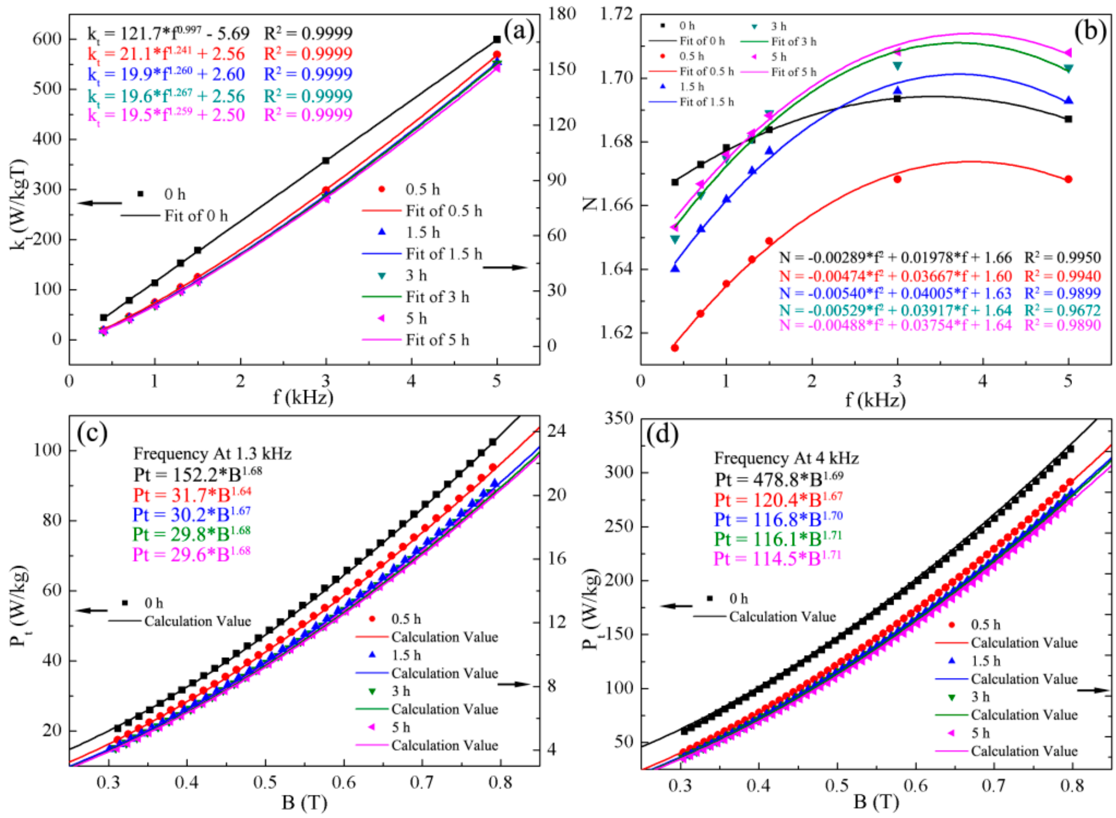

Figure 4. (a) AC iron loss coefficient kt and fit results; (b) AC iron loss factor N and fit results; The iron loss test result and calculation value at (c) 1.3 kHz frequency and (d) 4 kHz frequency.

In addition, the "AC Steinmetz law" ($P_t = k_{ac}B_m^n f^\alpha$) shows the total iron loss is affected by magnetic induction intensity and frequency. If this formula is used to predict the AC iron losses, first the exponent "n" value, "α" value and the coefficient "k_{ac}" should be fitted out from iron loss - magnetic induction intensity curves at a certain frequency or from iron loss – frequency curves at a certain magnetic induction intensity. However, at other frequency or magnetic induction intensity, the value of "n" and "α" will change. Here, we integrate the variable "f" into the coefficient "k_t" and determine the coefficient "k_t" and the exponent "N" of the formula - $P_t = k_t B_m^N$ by fitting.

Further to find out the dependence of "k_t" and "N" on the frequency by fitting. Thereby we can predict the iron loss at other frequencies according to the formula - $P_t = k_t B_m^N$.

And when designing a core for using at a certain frequency or a certain frequency range, the core loss and magnetic induction intensity are important indicators. Based on some iron losses data and fitting results, designers can calculate the iron losses at different frequencies according to the formula - $P_t = k_t B_m^N$. The design of magnetic induction intensity is not only related to the composition and structure of the magnetic material, but also to the upper limit of the design of the iron loss. According to the requirements of iron loss, designers can also calculate the design of magnetic induction intensity.

4. Conclusions

Magnetic properties of the melt-spun Fe-6.5wt.%Si ribbons are investigated before and after heat treatment at 1000 ℃. DC properties are greatly improved, as well as the iron loss in the frequency range of 400 Hz to 10 kHz. Above 10 kHz, the melt-spun ribbons exhibit lower total iron loss compared with the annealed one.

A simplified formula based on Steinmetz law is proposed and verified to predict the AC iron loss for high silicon steel ribbons in the range of 400 Hz to 5 kHz and the results are presented in this paper According to iron losses data, "k_t" and "N" of the simplified formula - $P_t = k_t B_m^N$ can be determined, and the AC iron losses can be predicted. The method developed in this work could be used for other magnetic materials to predict AC iron loss with great ease.

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Conflicts of Interest: The authors declare no conflict of interest.

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