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Effect of Ball Scribing on Power Loss Separation of Fe-3%Si Grain-oriented Silicon Steel

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Abstract: Power loss of Fe-3%Si grain-oriented silicon steel was measured after ball scribing with different spacing using a self-designed tool. Three different sections of power loss, including hysteresis loss, abnormal loss, and eddy current loss, were measured and calculated, respectively. The loss variation and ratio were analyzed based on the experimental data. At 1.0 T, hysteresis loss of tested steel with scribing spacing of 8 mm descends by 8.2% compared to samples without scribing, which is similar to the total loss variation, and abnormal loss descends by 16.8%. At 1.0 T, hysteresis loss ratio of the steel with scribing spacing of 16 mm ascends from 55.7% to 57.9%, and eddy current loss increases from 17.4% to 24.1%, while abnormal loss descends from 26.9% to 23.7%. The experimental results show that the reduction of power loss after scribing is mainly due to decreasing of hysteresis loss and abnormal loss.

Key words: Fe-3%Si grain-oriented silicon steel; ball scribing; hysteresis loss; eddy current loss; abnormal loss

1 Introduction

As a kind of significant soft magnetic material, silicon steel is widely used in transformers, motors and electromagnetic switches[1,2]. Grain-oriented silicon steel is an appropriate material for large transformers and generators due to its advantages of energy-saving and weight-lightening, and grain-oriented silicon steel becomes promising for large-scale nuclear and thermal power plants[3,4]. Thousands of tons of silicon steel are annually used in wound cores in electromagnetic devices. Excellent magnetic properties also make conventional grain-oriented silicon steel suitable for iron core of directional magnetic field, in order to reduce power loss and increase magnetic induction[5].

High magnetic flux density and low power loss are two primary targets for researchers to explore and develop silicon steel. Increasing concern of scientific community towards grain-oriented silicon steel due to its excellent magnetic and mechanical properties has raised the issue of power loss reduction[6]. Some research has been carried out related to rolling process and surface treatment which could help reduce power loss[7,8], and two effective methods are improving the orientation degree and optimizing chemical components. Moreover, there are two other potential aspects: more average domain wall movement and more efficient domain refinement. Effective methods to improve domain refinement include developing new coating, improving scribing methods and optimizing strain structure[9-11].

A ball scribing technique was developed by European Electrical Steels to avoid the re-coating problem, and some research has been carried out applying such a technique[12]. In this technique a steel

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ball is pressed onto the steel surface, and a region of permanent plastic damage is produced after scribing[13]. Though this method is not anneal proof, it dose not disrupt the steel coating, therefore, it is appropriate for transformer core plate installation without re-anneal, and the problems such as high magnetostriction and noise, low lamination factor could also be effectively avoided. The origin of power losses and their separation play an important role in the application especially in silicon steels[14]. However, effects of scribing on power loss separation in silicon steel were rarely studied. Based on calculation methods discussed in other literatures and experimental data, effect of ball scribing on power loss separation was investigated in this paper.

2 Experimental

Chemical composition of Fe-3%Si grain-oriented silicon steel is shown in Table 1.

Table 1 Chemical composition of tested materials

Elements	Si	C	Mn	S	Cu	P	Al	Fe
wt%	3.09	0.054	0.072	0.018	0.075	0.015	0.010	Bal

Standard Epstein samples with dimensions of 350 mm×30 mm×0.3 mm were prepared. Magnetic properties of test steel are shown in Table 2.

Table 2 Initial magnetic properties of test steel at 1.0 T

Properties	Power loss / (W/kg)	Coercive force /(A/m)	Relative permeability	MBNrms /mV
Value	0.711	282.9	799.4	0.391

In this paper ball scribing was achieved by a self-designed ball scribing instrument, by which scribing spacing of 2 mm, 4 mm, 8 mm, and 16 mm was achieved. The scribing direction was perpendicular to the rolling direction. A standard test Epstein strip was placed between the yokes, and a feedback control system implemented in LabVIEW was used to control the flux density to have repeatable and comparable measurements. Each strip was magnetised under sinusoidal flux density, and the peak flux density was from 0.1 T to 1.3 T at a magnetising frequency of 50 Hz. Each measurement of magnetic property was made three times and then averaged. Before each measurement each sample was drawn out and demagnetized. Temperature was controlled at 25 ℃ with an air conditioner to eliminate temperature disturbance. Computers for collecting data were placed in another room to avoid interference[15].

3 Results and discussion

3.1 Theoretical background

Statistical loss theory is a significant tool for estimating losses at different frequencies, which provides insight of reducing power loss and helps to estimate the loss under various working conditions. The power losses of silicon steel laminations can be described using the loss separation[16]. The total loss P_t is then expressed as the sum of three sections, the hysteresis loss (P_h), the eddy current loss (P_e) and the abnormal loss (P_a):

$$P_t = P_h + P_e + P_a \tag{1}$$

The hysteresis loss is mostly related to the microstructure of the steel, including grain size, precipitate distribution and texture. In the alternating magnetic field, P_h=HdB, and P_h is in proportion to the area of magnetic hysteresis loop. When the frequency is a constant, P_h is in proportion to coercive force, which can be expressed by the following formula[17]:

$$P_h = a \cdot B_m \cdot H \tag{2}$$

where, B_m is the peak induction, and H is the coercive force.

The eddy current loss is a dynamic loss, which can be derived from Maxwell's equations. For the slab geometry, sinusoidal induction and full flux penetration, the eddy current loss can be written as Eq.(3)[18]:

$$P_e = \frac{\pi^2 t^2 f^2 B_m^2 k^2}{6\rho\gamma} \tag{3}$$

where, γ is the electrical conductivity, t is the plate gauge, B_m is the peak induction, k is the sine wave constant, f is the frequency, and ρ is the mass density.

3.2 Power loss separation

In this paper, we could get B_m and H_c, and determination of a depends on the frequency variation method. After calculation a is determined as 0.0014 for Fe-3%Si grain-oriented silicon steel. Fig. 1 indicates that for Fe-3%Si grain-oriented silicon steel, hysteresis loss decreased after ball scribing. At 1.0 T, hysteresis loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 8 mm descends by 8.2% compared to samples without scribing. Such variation trend is also similar to the total loss variation, as the peak flux density increases, hysteresis loss rises. Domain scribing spacing of 8 mm achieves the lowest hysteresis loss, such a result indicates that optimum scribing spacing relates closely to influencing factors of resistivity, magnetic domain wall energy density, peak flux density, thickness of the sheet, and magnetizing frequency[19].

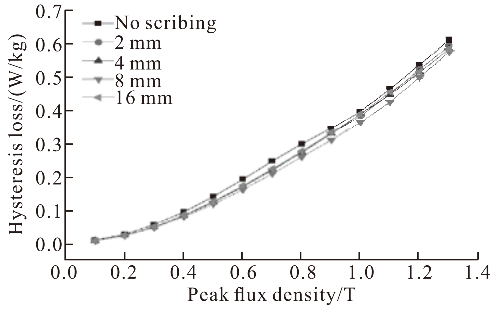

Fig.1 Hysteresis loss of Fe-3%Si grain-oriented silicon steel

In this experiment, t=0.3 mm, f=50 Hz, and k=1.11. For Fe-3%Si grain-oriented silicon steel, $\gamma=4.8\times10^{-4}$ Ω·mm, ρ=7.65 g/cm^3, thus eddy current loss of Fe-3%Si grain-oriented silicon steel can be expressed more easily if the equations are written as Eq.(4):

$$P_e = 0.124 B_m^2 \tag{4}$$

It is noted from Eq.(4) that P_e is proportional to B^2_m, and P_e is not affected by ball scribing.

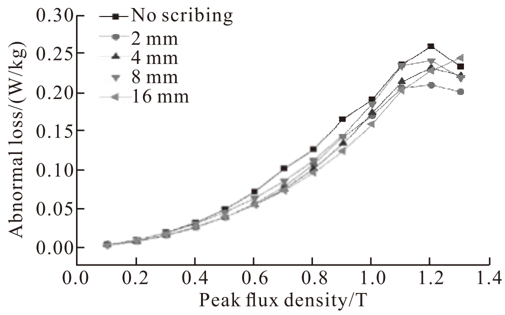

Fig.2 Abnormal loss of Fe-3%Si grain-oriented silicon steel

Abnormal loss could be calculated according to Eq.(1), as total loss, hysteresis loss and eddy current loss were measured and calculated. Fig.2 indicates that for Fe-3%Si grain-oriented silicon steel, power loss decreased after ball scribing. At 1.0 T, abnormal loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm descends by 16.8% compared to samples without scribing. When peak flux density is above 1.1 T, abnormal loss no longer increases with peak flux density. Such variation indicates that as peak flux density is increasing, abnormal loss will not rise as hysteresis loss and eddy current loss. At a certain flux density, abnormal loss will maintain at a certain level, such variation may be related to peak polarization and the influence of the full saturation on the domain wall process which is closely proportional to abnormal loss in magnetizing process[17].

3.3 Domain wall energy analysis

Analysis of experimental results could be based on theory of domain and energy of domain wall. After ball scribing, new secondary magnetic domains take shape along the scribing lines of the grain-oriented silicon steel, which is mainly due to the compressive stress where plastic deformation forms along the scribing lines[19]. As shown in Fig.3, static domain patterns observed on surface of silicon steel before and after ball scribing were compared. After the ball scribing the magnetic domains has been refined apparently. At the pinning sites introduction of scribing lines divides magnetic domains.

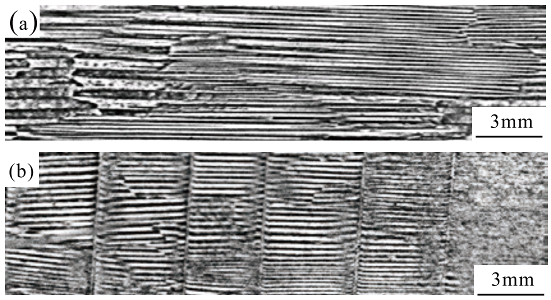

Fig.3 Static domain patterns observed on surface of silicon steel (a) before and (b) after ball scribing

Increase of equilibrium distance between domain walls makes power loss rise. The compressive stress also generates surface free magnetic poles, and the magnetic elastic energy increases. Transverse secondary magnetic domains form, and spiky secondary magnetic domains form in order to reduce magnetostatic energy caused by surface free magnetic poles. However, these secondary magnetic domains which are generated from primary magnetic domains are not stable, thus they absorb former primary magnetic domains and grow rapidly, and new primary magnetic domains form. Through the development of free magnetic poles and secondary magnetic domains due to compressive stress after ball scribing, primary magnetic domain spacing of silicon steel becomes smaller, which reflects the reduction of both hysteresis and abnormal power loss in the macroscopic magnetic properties.

3.4 Power loss ratio calculation

As can be seen from Fig.4(a), except scribing spacing of 8 mm, scribed Fe-3%Si grain-oriented silicon steel samples show an increase in hysteresis loss ratio. As peak flux density increases, hysteresis loss first drops, then increases while peak flux density is above 1.1 T. At 1.0 T, hysteresis loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm ascends from 55.7% to 57.9%.

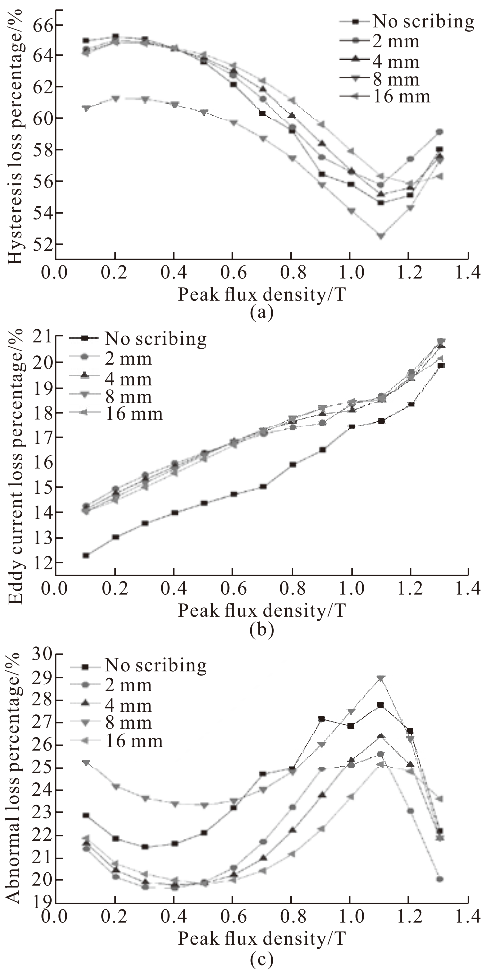

Fig.4 Different loss ratio to total power loss of Fe-3%Si grain-oriented silicon steel: (a)hysteresis loss; (b)eddy current loss; (c)abnormal loss

Eddy current loss ratio of Fe-3%Si grain-oriented silicon steel in total power loss was calculated. Fig.4(b) shows the eddy current loss percentage variation, and it is noted that after scribing, eddy current loss percentage in total loss ascends apparently, different scribing spacing shows similar increasing trend. As peak flux density increases, eddy current loss percentage increases gradually. The increase of eddy current loss ratio in total power loss is mainly due to the fact that total power loss has declined after ball scribing for Fe-3%Si grain-oriented silicon steel, while eddy current remains unchanged. At 1.0 T, eddy current loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm ascends from 17.4% to 24.1%.

As can be seen from Fig.4(c), except 8 mm scribing spacing, scribed Fe-3%Si grain-oriented silicon steel samples show a decrease in abnormal loss ratio. As peak flux density increases, abnormal loss first drops at 0.3-0.5 T, then increases to top ratio at 1.1 T, then falls again. At 1.0 T, power loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm descends from 26.9% to 23.7%.

Through comparison of hysteresis loss, eddy current loss and abnormal loss ratios given in Fig.4, it is noted that eddy current loss ratio apparently increases and abnormal loss ratio decreases except samples 8 mm scribing width, such special ration status indicates the existence of optimum scribing spacing, which also confirms the domain analysis during the magnetization process above. 1.1 T could be seen as a critical peak flux density to distinguish the increase or decrease trend of both hysteresis and abnormal loss ratio, which also provides reference for further research on characteristics and application of three different power loss sections. After scribing, hysteresis loss ratio of Fe-3%Si grain-oriented silicon steel ascends. In the process of power loss reduction caused by ball scribing, eddy current loss and hysteresis loss increasingly become more significant during magnetizing process.

4 Conclusions

a) Hysteresis loss declined after ball scribing. At 1.0 T, hysteresis loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 8 mm descends by 8.2% compared to samples without scribing, which is similar to the total loss variation. Hysteresis loss ratio of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm ascends from 55.7% to 57.9%.

b) Eddy current loss of Fe-3%Si grain-oriented silicon steel can be simplified as Eddy current loss is not affected by ball scribing, but its ratio in total loss rises apparently. At 1.0 T, eddy current loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm ascends from 17.4% to 24.1%.

c) Abnormal loss of Fe-3%Si grain-oriented silicon steel sharply decreased after ball scribing. At 1.0 T, abnormal loss of Fe-3%Si grain-oriented silicon steel with scribing spacing of 16 mm descends by 16.8% compared to samples without scribing, and the ratio descends from 26.9% to 23.7%.

d) Peak flux density of 1.1 T could be seen as a critical point to distinguish the increase or decrease trend of both hysteresis and abnormal loss ratios, which also provides reference for further research on characteristics and application of three different power loss sections.

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