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Effect of non-metallic precipitates and grain size on core loss of non-oriented electrical silicon steels

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ABSTRACT

In the current study, the number density and size of non-metallic precipitates and the size of grains on the core loss of the 50W800 non-oriented electrical silicon steel sheets were investigated. The number density and size of precipitates and grains were statistically analyzed using an automatic scanning electron microscope (ASPEX) and an optical microscope. Hypothesis models were established to reveal the physical feature for the function of grain size and precipitates on the core loss of the steel. Most precipitates in the steel were AlN particles smaller than 1 μm so that were detrimental to the core loss of the steel. These finer AlN particles distributed on the surface of the steel sheet. The relationship between the number density of precipitates (x in number/mm^2 steel area) and the core loss ($P_{1.5/50}$ in W/kg) was regressed as $P_{1.5/50} = 4.150 + 0.002\,x$. The average grain size was approximately 25–35 μm. The relationship between the core loss and grain size (d in μm) was $P_{1.5/50} = 3.851 + 20.001\,d^{-1} + 60.000\,d^{-2}$.

1. Introduction

The non-oriented electrical silicon steel is an essential magnetic material well used as the materials for rotors for different motors and generators, especially in energy, machinery and electricity fields [1–4]. With the increase of the global electricity energy consumption, requirements for high-quality non-oriented electrical silicon steel are becoming serious more and more [5]. Core loss is an important feature to judge the quality of non-oriented electrical silicon steel sheets, and a low value of this parameter leads to a better efficiency of energy utilization, a decrease in heat generation, and leads to downsize motors and improve service life simultaneously [6]. Factors which have influences on the core loss the steel can be classified into two major parts: non-metallic precipitates and properties of the material including crystallographic texture, chemical composition, microstructure and grain size [7–11]. It is an essential way to decrease the core loss by decreasing the number density of non-metallic precipitates and improving the grain size, whose boundaries block the motion of domain wall during magnetization [12]. Studies were reported to investigate the effect of non-metallic precipitates and grain size on the core loss of steel [13–18]. However, only qualitative conclusions were obtained since too many parameters were involved to carry out quantitative analysis. Furthermore, most quantitative analysis on the grain size and core loss are short of theoretical fundamentals and the physical feature of grains on the core loss were hardly revealed. Recently, Pirgazi [2] established a mathematic model showing the relationship between magnetic induction and grain size of the steel. Mathematic equation between grain size and core loss can be obtained using the developed model. Furthermore, it is known that the coercivity is in direct proportion to the core loss and the number density of non-metallic precipitates. Meanwhile, it is in inversely proportion to the size of precipitates, hinting that the relationship between precipitates and core loss can be regressed into a linear equation.

In the current study, the effect of non-metallic precipitates and grain size on the core loss of a non-oriented electrical silicon steel were quantitatively investigated using an automatic scanning electron microscope (ASPEX) and optical microscope. The statistical feature of non-metallic precipitates and grain size of the steel were obtained. Furthermore, hypothesis models on the eddy current loss, as well as hysteresis loss, and grains were established.

2. Materials and experiments

Eight samples of 50W800 non-oriented electrical silicon steel product sheets fabricated by one-step-cold-rolling technique were the analyzed in this study. The thickness of samples is 0.5 mm. The manufacturing process and parameters of the samples are similar.

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The equivalent Si content (Si% + Al%) of these samples are about 1.3 wt%, and their core loss are listed in Table 1. The core loss is measured by MTR-2949 alternating current magnetization characteristic measuring device from METRON Tech Research Corporation, Japan whose accuracy can reach to 0.0001 W/kg with a maximum error of 0.0016%.

The main devices in this study are ASPEX SEM and Leica DM 4000 optical microscope (OM). The minimum equivalent size of the detected precipitates can reach to under 0.1 μm by using ASPEX SEM and the optical micrographs of grain were taken by OM.

Polished samples were exposed to ASPEX and abundant data including precipitate size, number density can be gained by automatic scanning. Then, the samples were etched by 4%-nitric-acid ethanol solution. The average grain size can be counted using Image-pro plus software (IPPS). Fig. 1 shows the method for counting grain size by IPPS.

First of all, the scale of the pictures of grains should be the same. After dealing the picture by graphics software such as PS and inputting the scale into IPPS, the real grain size of each sample can be directly obtained by IPPS. Then, the square mean was computed with the grain size just gained to know the average grain size. To improve the accuracy of the average grain size, more than 10 optical micrographs should be counted for each sample. Eq. (1) shows the formula to calculate the average grain size.

$$\bar{D} = \sqrt{\frac{4\sum S_i}{\pi n}} \tag{1}$$

where $\bar{D}$ is average gain size of each sample, S_i means the area of each grain which can be given by IPPS directly, n is the total grain number.

3. Effect of non-metallic precipitates on core loss of the steel

The magnetic property can be detrimentally influenced by precipitates through three ways: raising the inner stress induced by lattice distortion caused by precipitates; blocking the motion of domain wall during magnetization; inhibiting grain growth which is an indirect way to affect magnetic property [8]. It was reported that precipitates whose size is close to the thickness of domain wall have the strongest pinning effect on the grain growth and the motion of domain wall during magnetization [18]. The particles with the critical size about 30–100 nm have the strongest pinning effect. However, some studies [15,19] have focused on the effect of larger precipitates (>0.1 μm) on magnetic property, showing that these larger precipitates can also give damage on the motion of domain wall due to the raising of inner stress. In this study, the intersection of rolling direction (RD) and transverse direction (TD) of samples were scanned in order to count the number of precipitates. Fig. 2 shows the distribution of precipitate size and Fig. 3 shows the relationship between average number density of precipitates and core loss.

As shown in Fig. 2, most precipitates have a diameter smaller than 1 μm which is considered to be the critical size having detrimental effect on the motion of domain wall during magnetization of these samples. With the number density of these precipitates increasing, the core loss grows up obviously. As mentioned above, core loss is in direct proportion to the number density of precipitates and in inversely proportion to precipitate size. Since the average precipitate size can be regarded as 0.3 μm now, the equation of precipitate and core loss can be regression analyzed by the linear equation where the number density of precipitates was assumed as the only variable. Eq. (2) is the regression equation between number density of precipitates (<1μm) and core loss and Fig. 3 shows their graphic relationship.

$$P_{1.5/50}(\mathrm{W/kg}) = 4.14988 + 0.002\mathrm{x}(\mathrm{number/mm^2}) \tag{2}$$

As shown in Fig. 3, if there are 100 more precipitates (<1μm) per mm^2, core loss will increase by 0.2 W/kg. Precipitates will raise the dislocation density of grain and hinder the motion of domain wall during magnetization, raising the coercivity and then impact the core loss.

To identify the source of finer precipitates, the intersection of rolling direction (RD) and normal direction (ND) of samples were scanned in order to know the distribution of precipitates in ND. Fig. 4 shows the typical distribution of precipitates on RD-ND plane of samples.

As shown in Fig. 4, the smaller precipitates whose size are smaller than 1 μm prefer to locate on the layers of samples in normal direction while the larger precipitates tend to distribute in the interior of samples. These layers which contain a plenty of smaller precipitates on the surface of samples are thought to be nitriding layer according to the composition analysis of precipitates shown in Fig. 5.

As shown in Fig. 5, smaller precipitates with a diameter smaller than 1 μm are most AlN particles. These nitriding layers may be generated in the final annealing process where the air atmosphere contains nitrogen. Non-oriented electrical silicon steel is a kind of ultra-low sulfur steel which has a close affinity to nitrogen. The nitrogen atoms can be absorbed from the annealing atmosphere into the interior of steel sheet and combine with aluminum atom, resulting in finer AlN precipitates appearing on the surfaces of steel sheet and lead to remarkable rise in hysteresis loss. This nitriding process will be promoted by bringing down the sulfur contain or raising final annealing temperature [20]. Fig. 6 is the typical morphology of finer AlN particles in samples.

Most finer AlN particles are rod-like in samples. The flat precipitates have a stronger effect on the motion of domain wall than circular precipitates during magnetization which may be due to the major axis of precipitates having a chief blocking effect on domain wall [21].

Generally, the precipitates with a diameter smaller than 1 μm are thought to have the strongest damage to core loss in these samples. These precipitates are mainly AlN particles and distribute on the surface of steel sheet. The nitriding layers can be prevented by increasing hydrogen partial pressure in final annealing atmosphere or adding surface-enriching elements like P, Sb, Sn that will not affect grain growth [22]. According to Taisei's work [23], when the mass fraction of AlN particles is lower than 0.0024 wt%, there will be little effects on core loss caused by these precipitates.

4. Effect of grain size on core loss of the steel

The final grain size is determined by many factors such as final annealing temperature, soaking time, and precipitates [24,25]. Namely, precipitates degrade the speed of grain growth but don't determined the final grain size [21], for which the effects of grain size on core loss can be analyzed separated from that of precipitates. By using OM and IPPS, accurate data of grain size of each sample can be gained. Fig. 7 and Table 2 show the volume fraction of grains in different size and the average grain size of the samples.

Table 1
Core loss (W/kg) of sample steel.

Sample	$P_{1.5/50}$ (W/kg)	Sample	$P_{1.5/50}$ (W/kg)
A	4.1976	E	4.5666
B	4.7373	F	4.5831
C	4.4534	G	4.6887
D	4.3937	H	4.3941