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Effect of texture and grain size on the magnetic flux density and core loss of cold-rolled high silicon steel sheets

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ABSTRACT

The effects of texture and grain size on the magnetic flux density and core loss (50–20 kHz) of 0.23 mm-thick cold-rolled high silicon steel sheets are investigated by means of electron back-scattered diffraction (EBSD), loss separation, and anisotropy parameter (ε) calculation. A model of the hysteresis loss coefficient k_h considering average grain size and ε is established. The magnetic flux density at 800 A/m (B_8) is closely related to the volume fraction of η-fiber-oriented grains, while the magnetic flux density at 5000 A/m (B_{50}) is closely related to the volume fractions of γ- and λ-fiber-oriented grains in high silicon steel. The hysteresis loss of high silicon steel can be greatly reduced by increasing the grain size and optimizing the texture of the sheets. Although increases in frequencies decrease the effect of texture on core loss, the effect cannot be ignored. As annealing temperature and time increase, the relative difference in core loss between the rolling direction (RD) and the transverse direction (TD) is maintained at higher frequencies because of increases in grain size, decreases in γ texture, and maintenance of a strong η texture. Texture and grain size jointly affect the high-frequency core loss of high silicon steel.

1. Introduction

High-silicon steel (6–6.5% Si) is believed to be applicable to magnetic devices operating at high frequencies because its high permeability, low magnetocrystalline anisotropy, near-zero magnetostriction, low core loss, and low device noise [1]. However, increasing the silicon content in steel deteriorates the formability of the alloy because of the increased hardness [2]. As well, the appearance of ordered phases, including B2 and $D0_3$, which are formed on the basis of the fundamental bcc crystal lattice [3], results in embrittlement and raises the level of difficulty of material deformation by conventional rolling. To avoid mechanical processing, high-silicon steel sheets and ribbons are produced by other methods, such as chemical vapor deposition (CVD) [1,4,5], hot dipping [6], spray forming [7], and rapid solidification [8]. However, researchers have found that ordering may be avoided by using an appropriate thermomechanical procedure [9,10] and suppression of the ordering reaction by controlling the cooling rate after annealing [11–13]. In recent years, the toughness and ductility of high-silicon steel have been improved through the principles of deformation-induced softening and annealing-induced hardening in ordered solid solutions [14]. High-silicon steel sheets with superior magnetic properties have been successfully fabricated through hot rolling combined with warm and cold rolling, as well as appropriate intermediate heat treatment [15–18].

Although the magnetic anisotropy of high-silicon steel is lower than that of 3%Si steel (i.e., the magnetic anisotropy constant K_1 of 6.5%Si–Fe is lower than 3%Si–Fe by about 40%) and the saturation magnetic flux density B_s of 6.5%Si–Fe is 1.80 T while that of 3%Si–Fe is 2.03 T, the magnetic flux density of high-silicon steel may still be improved by optimizing its texture [19,20]. Compared with 3% silicon steel, high-silicon steel presents advantages of lower core loss at high frequencies. Scholars generally acknowledge the existence of an optimum grain size for minimizing core loss; here, optimum grain size decreases as resistivity decreases or frequency increases or the thickness of the steel sheet increases [21]. The effect of annealing temperature on the magnetic properties of cold-rolled high-silicon steel has been previously studied [15,16], and researchers mainly consider the influence of grain size but ignore the role of texture. Refs. [22,23] propose that controlling the formation of B2 and $D0_3$ ordered phases and lowering antiphase boundaries by using different heat treatments can reduce the loss of high-silicon steel at 60 Hz; however, the influences of these parameters on core loss at higher frequencies are not well known.

In this study, 0.23 mm-thick cold-rolled sheets of high-silicon steel were successfully produced by rolling. The effect of texture and grain size on the magnetic flux density and core loss (50–20 kHz) of cold-rolled high-silicon steel sheets were investigated. To

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differentiate the effects of grain size and crystallographic texture on core loss, loss separation and anisotropy parameter (ε, magnetic anisotropy energy parameter) calculations were performed.

2. Experimental materials and methods

The high-silicon steel ingot used in this study was prepared by melting pure iron and silicon in an induction vacuum furnace. A small amount of pure nickel and copper was added to the melt to increase the ductility and improve the workability of the resultant alloy. The chemical composition of the ingot is shown in Table 1.

The ingot was forged into a 20 mm-thick plate at temperatures ranging from 1050 °C to 900 °C, hot rolled to 2.1 mm thickness at temperatures ranging from 1150 °C to 800 °C, and then warm-rolled to 0.55 mm at temperatures ranging from 750 °C to 550 °C. Afterward, the warm-rolled bands were annealed at 850 °C for 20 min, quenched in oil, and then cold-rolled to 0.23 mm at 200 °C. The cold-rolled sheet was cut into samples measuring 50 mm × 50 mm. Samples 1, 2, 3, and 4 were annealed at 850, 950, 1050, and 1150 °C, respectively for 10 min. Samples 5 and 6 were annealed at 1150 °C for 60 min to study the effect of texture alone on core loss. All of the samples were annealed in the same atmosphere (H_2+N_2) and cooled in still air.

The texture of each sample was and analyzed by an Oxford Instruments HKL-Channel 5 EBSD system equipped with a Zeiss ULTRA55 scanning electron microscope. To improve statistical analysis, all textures presented in this paper were calculated from different areas of the samples containing over 1000 grains per sample. The magnetic flux densities at 800 (B_8) and 5000 (B_{50}) A/m along the rolling direction (RD) and typical core losses along the RD and transverse direction (TD), including $P_{10/50}$, $P_{15/50}$, $P_{10/400}$, $P_{10/1k}$, $P_{5/2k}$, $P_{2/5k}$, $P_{1/10k}$, and $P_{0.5/20k}$ ($P_{10/50}$ is determined at a magnetic flux density of 1.0 T and 50 Hz; the rest of the P values can be deduced by analogy), were measured by an electrical steel tester (MPG 200D). Typical high-frequency core losses were measured according to the product manual of Super Core (high-silicon steel) produced by JFE Steel Corporation; these typical high-frequency core losses have been described in many literature reports [2,24,25].

3. Results and discussion

The average grain size and magnetic flux density along the RD of all of the samples obtained after different annealing processes are shown in Table 2. The value of B_8 along the RD of the high-silicon steel sheets prepared in this study is higher than that produced by CVD [1,26]. Differences in magnetic flux density between samples in Table 2 are mainly related to variations in their textures. Fig. 1 shows the constant $\varphi_2=0°$ and $\varphi_2=45°$ sections of the orientation distribution functions (ODFs, φ_1, Φ and $\varphi_2=0$–$90°$) of all of the samples. Most of the samples feature strong η (⟨001⟩//RD) and λ [⟨001⟩//normal direction (ND)] textures and weak γ (⟨111⟩//ND) textures. After annealing at the same temperature and time, differences in texture between samples 5 and 6 are observed; these differences are attributed to variations in their initial textures before annealing because the samples were cut from different areas of one sheet and sample 5 was obtained from a location farther from the others. To analyze the evolution of texture with increasing annealing temperature and time, orientation densities along η-fibers ($\varphi_1=0°$, and $\varphi_2=0°$), λ-fibers ($\Phi=0°$, $\varphi_2=45°$), and γ-fibers ($\Phi=55°$, $\varphi_2=45°$) are obtained, as shown in Fig. 2. The volume fractions of η-, λ-, and γ-fiber-oriented grains are shown in Fig. 3.

Table 1
Chemical composition of the high-silicon steel ingot (wt%).

Element	C	Si	Ni	Cu	Fe
Content	0.01	6.4	0.4	0.1	Balance

Table 2
Average grain sizes and magnetic flux densities along the RD of samples 1–6 obtained after different annealing processes.

Sample	Annealing process	Average grain size (μm)	B_8 (T)	B_{50} (T)
1	850 °C × 10 min	38	1.426	1.624
2	950 °C × 10 min	58	1.417	1.607
3	1050 °C × 10 min	90	1.433	1.633
4	1150 °C × 10 min	140	1.431	1.645
5	1150 °C × 60 min	183	1.419	1.641
6	1150 °C × 60 min	180	1.426	1.648

Fig. 2 illustrates the changing trends of orientation density among the η, λ and γ fibers. As annealing temperature increases, the orientation density of η-fibers with a peak at {210}⟨001⟩-{310}⟨001⟩ first increases and then decreases; by comparison, the density of λ-fibers with a peak at {100}⟨310⟩-{100}⟨010⟩ gradually increases. In γ-fibers, only the {111}⟨112⟩ texture component density remains unchanged; the densities of other components along γ-fibers decrease such that the overall density of γ-fiber shows a reduction.

Comparison of the volume fractions of η-, λ-, and γ-fiber-oriented grains with the magnetic flux densities of all of the samples reveals a strong relationship between B_8 and the volume fraction of η-fiber-oriented grains: the larger the volume fraction of η-fiber-oriented grains, the higher the B_8 value. By contrast, B_{50} is more closely related to the volume fractions of λ- and γ-fiber-oriented grains than the η-fiber-oriented grains, and much stronger λ textures as well as weaker γ textures can help improve the value of B_{50}, because not all of the grains can reach saturation magnetization at the magnetic field strength of 800 A/m. Thus, samples containing more grains with the most easily magnetized ⟨100⟩ orientation have higher B_8. At the magnetic field strength of 5000 A/m, grains of ⟨100⟩ orientation reach saturation magnetization and the value of B_{50} depends on the proportion of {100} and {111} grains.

Fig. 4 shows the core losses of all of the samples obtained with different test parameters along the RD. The core losses of high-silicon steel sheets display an overall decreasing trend as annealing temperature and time increasing.

The core losses of all of the samples along the RD at a magnetic flux density of 1.0 T and frequencies of 50–1000 Hz are analyzed by classical loss separation theory. The total core loss (P_t) is decomposed into hysteresis loss (P_h), classical eddy current loss (P_e), and anomalous loss (P_a). According to the theory presented by Bertotti [26,27], the total core loss can be expressed by:

$$P_t = P_h + P_e + P_a = k_h f B^{\alpha} + k_e f^2 B^2 + k_a f^{1.5} B^{\beta} \tag{1}$$

where f is the frequency, B is the magnetic flux density, and the values of k_h, k_e, k_a, α, and β are assumed to be constants. When $B=1.0$ T

$$P_t = P_h + P_e + P_a = k_h f + k_e f^2 + k_a f^{1.5} \tag{2}$$

Eq. (2) is divided by the frequency to yield

$$P_t/f = k_h + k_e f + k_a f^{0.5} \tag{3}$$

The coefficient of k_h can by calculated by fitting the values of $P_{10/50}$, $P_{10/400}$, and $P_{10/1k}$ to Eq. (3) [26]; the P_h for each sample is then obtained by Eq. (2). According to the classical expression of eddy current loss deduced from the Maxwell equation