Effect of Annealing Temperature on the Texture and Magnetic Barkhausen Noise of a Non-oriented Electrical Steel (0.88 wt% Si) after Inclined Cold Rolling

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Abstract. Inclined cold rolling was employed in this study to process a 0.88 wt% Si non-oriented electrical steel. After conventional hot rolling and annealing, the steel was cold rolled at various angles (i.e. 0°, 45°, and 90°) to the hot rolling direction (HRD), and the cold-rolled steel sheets were then annealed at different temperatures from 600°C to 750°C for 30 seconds to investigate the effect of annealing temperature on the texture and magnetic response of the material. The texture was measured by electron backscatter diffraction (EBSD), and the magnetic response of the steel was evaluated by magnetic Barkhausen noise (MBN) analysis. It was found that all the cold-rolled steels partially recrystallize at temperatures below 750°C, but the progress of recrystallization differs in steels cold rolled at different angles to the HRD, i.e. samples rolled at 45° to the HRD recrystallize faster than those after conventional rolling (0° to HRD) or cross rolling (90° to the HRD). The initial cold rolling texture (mainly the <651>-fibre and <741>-fibre) may change to cube, rotated cube, rotated Goss or {111}<112> depending on the rolling scheme and the annealing temperature. The MBN root mean square values of the samples cold rolled at different angles to the HRD show substantial differences during the annealing process. At low annealing temperatures (600°C and 650°C), the anisotropy of MBN in the conventionally rolled steel is much higher than those after inclined rolling or cross rolling.

1. Introduction

Non-oriented electrical steels are widely used for the manufacturing of lamination cores for electric motors. The crystallographic texture of the final steel sheets has a considerable effect on the magnetic properties of the steel core, thus affecting the performance and energy efficiency of the motors. To improve energy efficiency and maximize the output torque of the motor, the steel core is required to possess low core loss and high permeability, which are affected by the chemistry, thickness, microstructure, texture and stress state of the sheets. The desired crystallographic orientations for electric motors are the <001>//ND (normal direction) fiber texture, which maximizes the easy <001> axes in the sheet plane. To achieve the desired magnetic properties, a good control of the steel making/alloying as well as the thermomechanical processing is necessary.

Annealing is usually the last step of the thermomechanical processing, and the microstructure and texture obtained from the final annealing process have a direct effect on the magnetic properties of the
lamination core. It has been shown [1] that it was quite challenging to produce the desired \( <001>/\langle ND \rangle \) texture through conventional rolling-annealing procedures. Thus in this research, an unconventional rolling process, i.e. *inclined cold rolling* [2], was adopted to alter the conventional cold-rolling texture by changing the starting texture before cold rolling. Inclined cold rolling differs from conventional rolling in that, the cold rolling is conducted at an angle to the *hot rolling direction* (instead of along the HRD as in conventional rolling), i.e. after conventional hot rolling, smaller plates were cut from the hot band at different angles to the HRD and cold rolled in a conventional manner [3]. In this way, the initial texture was conveniently altered (rotated around the ND) while the chemistry, microstructure and processing history of the material were kept the same. This enabled one to exclusively investigate the effect of initial texture on the final texture without changing other parameters.

Previous studies [2-4] have shown that using this method, it was able to produce a strong cube texture at some inclination angles. It was also noticed that, not only did the initial texture before cold rolling affect the final annealing texture, but the annealing conditions (e.g. temperature and holding time) also influenced the texture. Thus, in this study, a series of annealing temperatures (600°C, 650°C, 700°C, and 750°C) were selected to conduct the annealing experiments on the incline-rolled steel to investigate the effect of annealing temperature on the microstructure/texture and the magnetic properties of the steel. Moreover, different from conventional magnetic property measurements by standard Epstein frame technique [5] or single sheet method [6], the magnetic response of the steel in this study was measured by a relatively new technology, i.e. magnetic Barkhausen noise (MBN) [7-9], which enabled one to measure angular MBN response. The effects of the cold rolling scheme and annealing temperature on the magnetic Barkhausen noise were examined.

2. Material and Experimental Procedures
The material investigated in this study was a low silicon non-oriented electrical steel. The chemical composition of the steel was (wt%): 0.88 Si, 0.002 C, 0.31 Mn, 0.46 Al, 0.001 S and 0.01 P. Detailed procedures to melt and process the steel were shown elsewhere [2]. After conventional hot rolling and annealing, samples (180 mm × 50 mm × 2.5 mm) were cut from the hot band at 0°, 45° and 90° to the HRD and cold rolled to a thickness of ~0.5 mm (~78% reduction), which corresponded to conventional rolling (0°), inclined rolling (45°) and cross rolling (90°), respectively. The cold-rolled steel sheets were then annealed at various temperatures (600°C, 650°C, 700°C and 750°C) in an argon-protected environment for 30 seconds (with a heating rate of 500°C/h), and furnace cooled. EBSD scans were performed on the ND-RD (normal direction - rolling direction in cold rolling) sections using an EDAX OIM 6.2 EBSD system under a field emission gun scanning electron microscope. The textures (ODF’s) were then calculated from the orientation data using a harmonic series expansion method. The grain sizes of the recrystallized crystals were also calculated based on the EBSD data.

Magnetic Barkhausen noise technique was utilized in this research to evaluate the magnetic response of the material. MBN is a noise-like signal generated from a ferromagnetic material when an external magnetic field with varying intensity and/or direction is applied to the material [10]. MBN is closely related to the interaction between the motion of magnetic domain walls and the stress configuration and microstructural features in ferromagnetic materials [10]. The Barkhausen noise is usually detected as a voltage signal (in millivolts), and the MBN may be affected by a number of material characteristics, such as the presence of elastic, plastic or residual stresses, the microstructure of the material (carbon content, phases, precipitates, dislocations, grain boundaries, etc.), the hardness and texture, etc.

The MBN measurements were conducted on the surfaces of the cold-rolled and annealed samples using a commercial MBN analyzer [9, 11]. A general purpose sensor was employed for all the measurements. To eliminate the “lift-off” problem generally encountered in MBN measurements, a testing platform with three-dimensional translation, two-axis tilting and two-directional rotation was built, which made the measurements repeatable and reliable. A picture of the MBN system used for this study is shown in Figure 1. For each sample, the MBN signals were collected along all the directions (0°-360°) in the sheet plane, with an interval of 15°/30° to the cold rolling direction. The average value of the measurements in all the directions on each sample was then taken as the overall MBN. At each
direction, the measurement consists of 20 bursts of MBN and the average root mean square value of the 20 bursts was reported. The frequency and voltage used for the magnetic excitation were 125 Hz and 5 V, respectively. The raw MBN signals collected from the material were filtered to a frequency range of 0.1 - 1000 kHz. During data processing, these were further filtered to 10-1000 kHz to smooth the data [11].

![Figure 1. The magnetic Barkhausen noise analysis system used in this study.](image)

3. Results and Discussion

3.1. Crystallographic Texture

3.1.1. Cold deformation texture. When the steel plate was cold rolled at 0°, 45° and 90° to the hot rolling direction, the material was actually subjected to conventional, inclined and cross rolling, respectively. Although the starting microstructure was identical, due to the rotation (45° and 90° around ND) of the initial texture for inclined and cross rolling, the resulted deformation textures are noticeably different from conventional rolling (Figure 2). The maximum texture intensity after cross rolling is much higher than that after conventional rolling, while the texture intensity after inclined rolling is considerably lower than that after conventional rolling. Although the textures after the three rolling processes have common components such as rotated cube (⟨001⟩<110⟩), α-fibre (⟨011⟩//RD) and γ-fibre (⟨111⟩//ND), the relative intensities among these components are quite different. Conventional rolling produces a strong rotated cube texture (maximum intensity: 13.4), a relatively strong and continuous α-fibre, and a weak γ-fibre. Inclined rolling reduces the intensity of the rotated cube while enhancing the γ-fibre. Thus the texture is featured by a considerably lower maximum intensity but a more uniform distribution of components such as rotated cube, α-fibre and γ-fibre. The strongest texture is observed near the ⟨112⟩<110⟩ orientation on the α-fibre. A strong ⟨111⟩<110⟩ component on the γ-fibre is also produced, which is not obvious in either conventional rolling or cross rolling. Cross rolling created a very strong rotated cube texture (intensity: 21.3), but the γ-fibre and α-fibre are weakened.

3.1.2. Annealing microstructure and texture. The variations of the fraction of recrystallization and grain size with respect to the annealing temperature and cold rolling direction are illustrated in Figure 3. Below 750°C, the fractions of recrystallization under the same annealing temperature are quite different among the three cold rolling schemes (Figure 3a), especially after annealing at 650°C (varying from 45% to 77%). The relationship between the fraction of recrystallization and the annealing temperature for cross-rolled, conventionally-rolled and incline-rolled samples can be fitted to a linear, a 2nd order polynomial and a 3rd order polynomial function, respectively. Compared to conventional rolling, cross rolling retards
the recrystallization process since the fractions of recrystallization at all the temperatures are smaller than those after conventional rolling. By contrast, inclined rolling accelerates the recrystallization process, since the fraction of recrystallization under the same annealing temperature is higher than those after conventional rolling. Apparently, cold rolling at various directions to the HRD created different microstructures, textures and stored energies or different distributions of those in the steel, which, in turn, lead to different recrystallization behaviours during the annealing process. The fast recrystallization of the incline-rolled steel may be attributed to the strong \{111\}<110> texture in the deformed structure, which was associated with a higher stored energy and numerous nucleation sites for the start of recrystallization.

![Figure 2. The textures after cold rolling: (a) conventional rolling (0° to HRD), (b) inclined rolling (45° to HRD), (c) cross rolling (90° to HRD). φ₂ = 45° sections of the Euler space (Bunge notation).](image)

The grain size of the recrystallized crystals also shows considerable differences among the three rolling schemes (Figure 3b). At a low annealing temperature (600°C), the grain size is almost the same for the three schemes, but with the increase of the temperature, the grain sizes of conventionally and cross rolled samples increase gradually with the temperature, while that of the incline-rolled sample increases quickly at 650°C, then stops at 700°C, and finally increases again at 750°C. The final grain sizes after complete recrystallization (750°C) are also different: the cross-rolled steel has a considerably larger grain size (~34 µm) than that (~21 µm) after conventional rolling or inclined rolling. Thus, the cold rolling with different initial textures also induced different grain growth behaviours during the annealing process.

The variation of recrystallization texture at various annealing temperatures is shown in Figure 4. For the steel after conventional rolling, annealing at 600°C produces the cube and rotated cube textures on the 0-fiber, which are the desired textures for non-oriented electrical steels. There is also a \{110\}<665> component on the \langle110\rangle//ND fiber together with a weak rotated Goss texture. When the annealing temperature is increased to 650°C, the overall texture intensity is considerably increased and the rotated Goss texture is strengthened. In the meantime, a relatively strong cube texture is created and the rotated cube texture disappears. If the annealing temperature is 700°C, a very strong \{111\}<112> texture (on the γ-fiber) forms and, the cube texture becomes very weak. Apparently, annealing the conventionally rolled steel at this temperature should be avoided since it will generate the undesired \langle111\rangle//ND texture. If the annealing temperature is further increased to 750°C, a \{001\}<120> texture forms on the 0-fiber, and a rotated Goss is also produced.

The steel after inclined rolling (45° to the HRD) shows considerably different textures during annealing: when the annealing temperature increases from 600°C to 700°C, there is always a strong cube together with a relatively strong rotated Goss texture. When the annealing temperature is further increased to 750°C, the cube texture disappears, and a strong \{110\}<111> texture is produced on the \langle110\rangle//ND fiber. Essentially no γ-fibre is produced at any of the annealing temperatures. Thus inclined cold rolling can prevent the formation of the γ-fibre texture during the annealing process,
although in the deformed state, it has the strongest γ-fiber. Apparently, for incline-rolled steel, the optimum annealing temperature is 700°C since a strong cube texture can be produced.

Figure 3. Variation of recrystallization with respect to the annealing temperature: (a) fraction of recrystallization, (b) grain size of the recrystallized crystals.

Figure 4. Comparison of the recrystallization textures after annealing at various temperatures for the samples after conventional, inclined and cross rolling.

For the steel after cross rolling, annealing at 600°C produces a cube texture plus a fibre extending from (001)<140> on the 0-fiber to (110)<665> on the <110>//ND fiber. At 650°C, the texture on the
$\phi_2 = 45^\circ$ section is quite weak, although the maximum intensity (on other sections) is relatively high. Only a relatively strong rotated Goss texture is noticed. When the temperature is increased to 700°C, the rotated Goss texture is significantly strengthened, and a relatively strong cube component is also created. Further increasing the annealing temperature to 750°C, a very strong cube texture forms, and the rotated Goss texture is weakened. Again, no $<111>/ND$ component is formed if the annealing temperature is 650°C or higher. Apparently, for cross-rolled steel the optimum annealing temperature is 750°C because a strong cube texture forms at this temperature.

It is thus seen that, after cold rolling at different angles to the HRD, the deformed steels behave differently during the annealing process. To produce the required $<001>/ND$ texture, the steel after conventional should not be annealed at 700°C, because the texture produced is a very strong $(111)<112>$ component on the $\gamma$-fibre. On the other hand, for the incline-rolled steel, it is better annealed at 700°C since at this temperature, a strong cube component is produced. For the cross-rolled steel, annealing at 750°C is suggested since a strong cube texture can be produced.

3.2. Magnetic Barkhausen Noise

The original MBN signal recorded by the testing system is the distribution of the noise (a voltage signal) with respect to time (Figure 5). The raw data is usually smoothed and statistically analyzed, and a number of MBN parameters can be derived from the smoothed MBN envelope [11]. One of the most commonly used parameters is the root mean square (rms) of the MBN signal, which is the square root of the sum of all the voltages squared divided by the total number of events recorded. The MBN$_{\text{rms}}$ represents the overall intensity of the MBN signal, and the rms value of a complete MBN burst is fairly stable from one burst to another. In this research, the MBN$_{\text{rms}}$ is utilized to evaluate the magnetic response of the material. The MBN$_{\text{rms}}$ value is highly dependent on the stress state and the microstructure of the material. For example, the two MBN bursts (recorded from cold-rolled and annealed samples) shown in Figure 5 have significantly different shapes and peak voltages. The plastic deformation induced a huge amount of dislocations and residual stresses in the material, thus the MBN voltages are much higher than those from a completely recrystallized steel (with much less dislocations and stresses).

![Figure 5. Typical MBN bursts recorded from steel samples: (a) after cold rolling at 45° to the HRD, (b) after annealing at 750°C for 30 seconds.](image)

The angular MBN$_{\text{rms}}$ distributions with respect to the direction of magnetization for the steels after cold rolling at different angles to the HRD are shown in Figure 6. Although the overall MBN$_{\text{rms}}$ values after cold rolling with all the three schemes are quite similar (around 700), the angular MBN$_{\text{rms}}$ distributions after annealing at various temperatures are quite different. For the conventionally-rolled steel (Figure 6a), annealing at 600°C causes a considerable drop of the MBN$_{\text{rms}}$ at all the directions, but
the anisotropy of the MBN$_{\text{rms}}$ is similar to that after cold rolling, i.e. with a slightly larger MBN$_{\text{rms}}$ in the RD than in the TD. Increasing the annealing temperature to 650°C, the overall MBN$_{\text{rms}}$ values go back to the level of the cold-rolled steel. This is unusual as it is normally expected that the recrystallization of the steel would result in the decrease of the MBN because of the decrease of dislocation density and the release of stress. The reason for this abnormal increase of the MBN$_{\text{rms}}$ at 650°C is not clear. Further increasing the annealing temperature to 700°C and 750°C, the MBN$_{\text{rms}}$ values gradually decrease, and the degree of anisotropy is also reduced (the distributions are close to perfect circles). After complete recrystallization at 750°C, apparent MBN$_{\text{rms}}$ anisotropy is still noticed, but the polarity has changed, i.e. the minimum MBN$_{\text{rms}}$ is observed at 30°/210° from the RD, while the maximum MBN$_{\text{rms}}$ is seen at 120°/300° from the RD. The anisotropy observed in the completely recrystallized steel is mainly due to the magnetocrystalline anisotropy induced by the crystallographic texture [12].

Figure 6. Variation of the MBN$_{\text{rms}}$ with respect to the annealing temperature and the cold rolling scheme: (a), (b), and (c) angular MBN$_{\text{rms}}$ for the conventionally (0° to HRD), incline (45° to HRD), and cross rolled (90° to HRD) steels, respectively, (d) average MBN$_{\text{rms}}$ of all the directions.

The incline-rolled steel shows considerably different MBN when subjected to annealing (Figure 6b). At 600°C, although with the largest fraction of recrystallization (35%) among the three steels (Figure 3a), the measured angular MBN$_{\text{rms}}$ has essentially the same values as the cold-rolled steel, i.e. annealing at this temperature essentially does not change the MBN of the material, although the steel has already partially recrystallized. However, when the annealing temperature is increased to 650°C (the fraction of recrystallization reaches ~80%), the MBN$_{\text{rms}}$ suddenly drops to a very low level (i.e. from ~700 to ~420),
and further increasing the annealing temperature essentially does not change the MBN_{rms} anymore. It is also noted that the anisotropy of the MBN_{rms} is reduced. The MBN_{rms} values (~400) after complete recrystallization (750℃) are considerably higher than those (~320) of the conventionally-rolled steel annealed at the same temperature.

The MBN_{rms} of the steel after cross rolling is different from both conventionally and incline rolled samples (Figure 6c). Instead of having a maximum MBN_{rms} in the RD, this is observed at 30°/210° to the RD, and the minimum MBN_{rms} is seen at 120°/300° to RD. When the annealing temperature increases, the overall MBN gradually decreases (Figure 6d), i.e. there exists a correspondence relation between the MBN_{rms} and the annealing temperature. With the increase of the fraction of recrystallization, the anisotropy of the MBN_{rms} also changes, i.e. after complete recrystallization (750℃), the maximum MBN_{rms} is at 120°/300° to RD, while the minimum MBN_{rms} is at 30°/210° to RD. The change of the average MBN_{rms} with respect to the annealing temperature is shown in Figure 6d, which clearly shows the trends of the MBN after cold rolling using the three different schemes.

4. Conclusions

Cold rolling at different angles to the hot rolling direction produces noticeably different deformation textures that lead to different recrystallization behaviors during the annealing process. Upon annealing, the incline rolled steel recrystallizes considerably faster than the conventionally or cross rolled steels. However, the cross-rolled steel has the largest final grain size when the recrystallization is complete. The annealing textures are also quite different at different temperatures.

After complete recrystallization at 750℃, the cross-rolled steel forms a strong cube texture and the conventionally rolled sample shows a relatively strong {001}<120> texture, both being the desired textures. The steel after inclined rolling, however, does not produce such textures.

While the MBN_{rms} of the cross-rolled steel decreases gradually with the increase of the annealing temperature, the MBN_{rms} values of the conventionally rolled or incline rolled steels show some abnormal behaviors, i.e. the MBN_{rms} of conventionally-rolled steel after annealing at 650℃ goes back to the cold-rolled values, while the MBN_{rms} of incline-rolled steel is essentially constant with the increase of the temperature when the temperature is 650℃ or higher.

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