Cold Rolling Reduction Dependence of the Recrystallization Texture of 3% Si Non-oriented Electrical Steel

Lee Seil1,a and De Cooman Burno C.2
1POSCO Technical Research Lab., Pohang, South Korea
2Graduate Institute of Ferrous Technology POSTECH, Pohang, South Korea
apull@posco.com

Abstract. The effect of the amount of cold reduction on the crystallographic texture, the microstructure, and the magnetic properties of cold rolled and annealed 3% Si non-oriented (NO) Si steel has been studied. The results indicate that, at constant final thickness, the combination of initial hot-rolled sheet thickness and the cold rolling reduction had a significant influence on the B50 magnetic flux density. The initial thickness of the hot-rolled sheet did not affect the crystallographic texture of the as-hot rolled sheet and the annealed hot-rolled sheet. At constant final thickness, the combination of a larger hot-rolled sheet thickness and a higher cold rolling reduction resulted in the decrease of the B50 magnetic flux density. This was due to an increase of the {411}<148> and {111}<112> texture components intensity and a decrease of the {110}<001> texture component intensity.

1. Introduction
Non-oriented (NO) electrical steel sheet is a magnetic material used as a core material for electrical motors and generators. Modern electrical motors and generators require a combination of a high power density and low energy losses. The energy losses in NO steels (core losses) are consists of three components; hysteresis losses, eddy current losses and the anomalous losses. Addition of Si and Al alloy contents is the most effective method to reduce core losses because an eddy current losses are decreased by an increasing electrical resistivity. There are two more methods to reduce eddy current losses, such as (a) the reduction of the sheet thickness [1], and (b) the optimization of the crystallographic texture [2].

However, magnetic flux density property, which is linked to the power density, is decreased by the alloy additions and thickness reduction. The crystallographic texture improvement is the only method to compensate the decrease of a magnetic flux density property of a NO steel sheet. The improvement of the crystallographic texture of the NO steel sheet makes it, in principle, possible to simultaneously reduce the core losses and increase the magnetic flux density. It is well known that the magnetic properties of α-Fe are anisotropic: while the <100> axes are axes of easy magnetization, the <111> axes are axes of hard magnetization. When a NO electrical steel sheet has a large fraction of grains with one or more <100> axes in the sheet plane, the magnetization parallel to the sheet plane will be easier, the magnetic flux density will increase, and the losses will be reduced.

Current technology allows for the production of NO steel with a thickness in the range of 1.0mm to 0.10mm, corresponding to a cold rolling reduction in the range of 70% to 95%. An increase of the cold reduction could result in the development of crystallographic textures during recrystallization annealing that are suitable for NO electrical steel.
3% Si NO steel differs from ULC steels in two aspects. First, the alloy content of NO steel is significantly higher, and the addition of Si and Al suppress the phase transformation during cooling after the hot rolling. This affects the texture of the hot rolled sheet prior to the cold rolling process. Instead of a transformation texture, a mixed texture of ferrite plane strain and shear texture components are obtained. Hot rolled 3% Si steel is often given an intermediate annealing, which increases the average grain size to a few hundred microns. These coarse grains typically develop a weaker γ-fiber intensity.

2. Experimental procedure
The composition of the NO electrical steel used in the present study was Fe-3.5% (Si+Al)+0.3%Mn-0.01%P-0.004%C-0.002%N-0.001%S (in wt.%). The steel was hot rolled to a thickness of 2.9 mm, 2.5 mm, 2.0 mm, 1.6 mm and 1.4 mm in a 5 stand hot rolling mill. The reduction applied in each stand was in the range of 20% to 50%. The hot rolled sheets, sized 300 mm x 85 mm, were given an intermediate anneal prior to cold rolling. The sheet was heated to the annealing temperature using a heating rate of +20 °C/s, held isothermally over 1000°C to obtain similar grain size in all thickness samples and subsequently cooled in air. The annealing furnace atmosphere was N₂. The samples were pickled and cold rolled to the thickness of 0.5 mm, 0.35 mm, and 0.23 mm. The cold rolling reduction therefore varied in the range of 65% (1.60 mm → 0.50 mm) to 92% (2.90 mm → 0.23 mm). The annealing of the cold rolled sheet was carried out in a continuous annealing simulator. The annealing atmosphere was a 50% H₂ + 50% N₂ gas mixture. The annealing time was 90 seconds. The annealing temperature was about 1000 °C for samples.

Figure 1. (a) Schematic illustration X-ray analysis. (b) φ₂=45° ODF section for the hot rolled sheets, and the hot-rolled and annealed sheets.

Large area texture measurements on the hot rolled sheet samples and hot-rolled and annealed sheet were carried out using a Bruker D8 X-ray diffractometer (XRD) equipped with a Co target source operated at a voltage of 35kV and a current of 45mA. The XRD measurements were taken from sheet
samples as illustrated schematically in figure 1 (a). The orientation distribution functions (ODFs) were calculated from the \{110\}, \{200\}, and \{211\} incomplete pole figures using the series expansion method implemented in the HTEXTools Version 3 software.

The microstructures and texture of the samples were characterized by light-optical metallography (LOM) and electron backscattering diffraction (EBSD) measurements. The EBSD measurements were carried out on a JEOL JSM7001F FE-SEM equipped with a TSL Hikari EBSD set up, and the data were analyzed with the TSL OIM v7.0 software. The EBSD measurements were applied on longitudinal RD plane sections as defined by the rolling and the normal direction.

The microstructure of the hot-rolled, hot-rolled and annealed, and cold-rolled steels was obtained by LOM. The measurements were carried out on the longitudinal sections, defined by the rolling direction and the normal direction. The samples were polished and etched in a Nital solution (5 vol% Nitric acid and 95 vol% ethanol).

The magnetic properties of the sheet samples were measured in a BROCKHAUS Messtechnik MPG 200 single sheet tester with a 60 mm x 60 mm yoke. The magnetic flux density properties of samples at 5000 A/m (B50) were measured along both the rolling and transverse directions.

3. Results and discussion

The φ2=45° section of the ODFs of the hot rolled and hot-rolled and annealed sheet is shown in figure 1 (b). The texture of hot rolled sheet was composed of the \{110\}<001>, \{110\}<112>, \{100\}<011>, \{112\}<110> and \{112\}<111> texture components. The texture of hot-rolled and annealed sheets consisted mostly of \{110\}<001>, \{112\}<110> and \{112\}<111> texture components. The intensities of the various texture components did clearly not differ between the hot rolled sheets and annealed sheets. This implies that differences in hot rolling reduction do not significantly affect the texture after hot rolling and after the annealing.

![Figure 2. LOM micrographs of the cold rolled steel (Nital etch)](image)

Fifteen samples with different cold rolling reductions were obtained and shown in figure 2. The sheets were cold rolled to a final thickness of 0.23 mm, 0.35 mm, and 0.5 mm. In the resulting set of samples, some of the cold rolled samples had a similar cold rolling reduction but a different final thickness. For example, the samples which were given a 82.8% were reduced in thickness were obtained from the samples having thicknesses of 2.9 mm, 2.0 mm, 1.4mm and cold rolled to 0.5 mm, 0.35 mm, 0.23mm, respectively. In general, the microstructure consisted of a dark etched region and a light etched region. The samples which were given a cold rolling reduction less than 79%, had in-grain deformation bands which extended from grain boundaries into the grain matrix. This microstructure resulted in dark etched regions. The deformation bands were more frequently observed when the cold rolling reduction increased from 65 % to 75%. In samples which were given a more severe reduction, i.e. >79%, no
deformation bands were observed. With increasing cold rolling reduction, the grains developed a pancaked shape when the cold reduction was more than 90%, i.e. all the grains were flattened parallel to the rolling plane. It is clear that the microstructure is determined by the cold reduction ratio rather than the difference in the final cold rolled sheet thickness.

Figure 3 reviews the texture of the samples after the complete 90s annealing treatment. The recrystallized grain size was typically larger than 70 µm. The texture was measured by analysing a 5mm x 5mm area of each sample by means of the EBSD technique. The {111}<112> texture component, the α*-fiber, and the {114}<148> texture component developed with increasing cold reduction. Texture components close to the {110} <001> orientation developed when the cold rolling reduction was less than 80%. The {110}<001> texture component was not observed in the samples which were given a cold rolling reduction larger than 80%. The α-fiber {112} <011>, {111} <011> and {100} <011> texture components, which were present after cold rolling, did not develop during annealing. The maximum texture intensity value increased with increasing cold rolling reduction, from 3.2 at 65%, to 6.4 at 92%. The maximum texture intensity after recrystallization annealing was observed near the {411}<148> orientation for the cold rolled sample which was given a 92.1% rolling reduction.

![Figure 3. φ_α=45° ODF sections, obtained from EBSD data, after a full recrystallization anneal.](image)

Figure 4 shows that the volume fraction of grains with the {411}<148> orientation increased significantly with increasing reduction. The intensity of the {411}<148> component increased continuously during annealing. This was especially pronounced for the samples with a 0.23mm final thickness. The fraction of {411}<148> oriented grains continued to increase during the grain growth stage following the recrystallization. The volume fraction of {411}<148>-oriented grains showed a clear tendency to increase for higher annealing temperatures and for larger grain sizes. While the {111}<112> orientation remained an important texture component after annealing, the volume fraction of the grains with this orientation was approximately half the volume fraction of the {411}<148>-oriented grains after annealing. The volume fraction of {111}<112>-oriented grains decreased with increasing annealing temperature.
Figure 4. Annealing temperature dependence of the volume fraction of the (a) \{110\}<001>, (b) \{111\}<110>, (c)<111>{112}, and (d) \{411\}<148>-oriented grains.

Figure 5. Effect of the cold reduction on (a) the B_{50} magnetic flux density values of averaged values, (b) the B_{50} magnetic flux density in the rolling direction, and (c) the B_{50} magnetic flux density in the transverse direction.

Figure 5 shows the cold rolling reduction dependence of the magnetic flux density B_{50} values. Regardless of the final thickness of the cold rolled sheets, the averaged magnetic flux density decreased with increasing reduction when the reduction was larger than 82%. The B_{50} values measured in the rolling direction decreased continuously with cold rolling reduction for reductions in the range of 65% to 92%. The value of B50 measured in the transverse direction first increased for reductions up to 82%, and decreased for larger reductions.

4. Conclusion
The effect of the cold reduction on the development of the crystallographic texture, the microstructural evolution, and the magnetic properties of cold rolled and recrystallization annealed 3% Si NO steel was investigated by OM, XRD and EBSD measurements. The texture of the hot-rolled sheet and the annealed hot-rolled 3% Si NO sheet is not affected by the hot-rolling reduction. The volume fraction of \{411\}<148>-oriented grains after an annealing increases with increasing cold rolling reduction. The magnetic flux density decrease is significant for cold rolling reductions exceeding 82%.

References
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