Formation of the primary recrystallization texture in the oriented electrical steel with 3% Si

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Abstract: The microstructure and texture of the cold rolled oriented electrical steel with 3% Si after annealing at various temperatures were characterized by means of electron backscattering diffraction (EBSD), scanning electron microscope (SEM) and X-ray diffractometer (XRD). It was found that the preferential nucleation sites are shear bands and the deformed grain boundaries at the early stage of the recrystallization. But the nuclei at the shear bands became to the dominated recrystallized grains with annealing. According to the experimental data and calculation results using misorientation principle, the misorientation between recrystallized grains and the surrounded deformed matrix was mainly distributed in the range between 25 and 45°. High stored energy of the deformed γ-fiber components results in preferred recrystallization at the beginning of recrystallization. The recrystallized grains oriented with {111}<110> and {111}<112> maintain prominent from beginning to the end of the recrystallization. The proportion of sporadical Goss recrystallized grains is low after completion of the recrystallization. But the misorientation between Goss grains and the surrounded grains is based on the high angles ranging from 25 to 45°.

1. Introduction
Oriented electrical steel is widely used as a soft magnetic material and its excellent electromagnetic property is closely related to the Goss texture {110}<001> component[1]. The Goss texture become significant during secondary recrystallization by abnormal grain growth, which the Goss oriented grains formed in the process of primary recrystallization grow preferentially and consume their adjacent grains with γ-fiber (<111>/normal direction) orientation[2]. The mechanism responsible for the abnormal growth of Goss oriented grains has been received much attention. There are generally two kinds of model to explain preferential growth of Goss oriented grains during secondary recrystallization. Firstly, it is assumed that the occurrence possibility of Σ3-Σ9 coincidence site lattice (CSL) boundaries around Goss grains is about 13% after completion of primary recrystallization. Due to the high mobility of these CSL boundaries, the grains with Goss orientation expand quickly with annealing and therefore lead to significant Goss texture[3,4]. Secondly, the grain boundaries with misorientation angle between 25° and 45° which show high energy play an important role on the growth of Goss oriented grains[5]. Therefore, the primary recrystallization texture and misorientation
distribution have a significant influence on the abnormal growth of the Goss oriented grains[6]. In this case, the study in forming mechanisms of primary recrystallization texture benefits the understanding of the orientation environment around Goss oriented grains which affect the formation of Goss texture during secondary recrystallization in oriented electrical steels.

One of two main theories responsible for the formation of primary recrystallization texture is oriented nucleation theory brought up by Burgers[7]. It has been claimed that the recrystallization texture originate from the nuclei of particular orientation. The other one is referred as oriented growth based on the assumption that the specific rotation relationships between recrystallized nuclei and deformed matrix are associated with rapid grain boundary migration[8]. It was observed that the recrystallized nuclei show preferential orientation. Furthermore, specific misorientation between nuclei and deformation matrix exhibit high migration rate during the process of grain growth. In the current work, the orientation relationship between recrystallized grains and deformed matrix were studied by means of SEM and EBSD.

2. Experimental Procedure

The material used in the current work is a commercial oriented electrical steel with the chemical composition listed in Table 1. The thickness of as-received hot rolled slab is about 3 mm. The slab was heated at 1000°C for 5 minutes in N2 atmosphere and then cold rolled to 0.6 mm (75% reduction) using a laboratory mill. Subsequently, the cold rolled sheets were annealed at various temperatures ranging from 650°C to 770°C for 3 minutes in N2 atmosphere. The volume fraction of recrystallization was obtained at different stage of annealing by HKL Channel 5 and Image Pro Plus software.

Table 1. The chemical composition of the oriented electrical steel (in wt.%)

| C  | Si  | Mn | P  | S  | Al | Cu  | N  |
|----|-----|----|----|----|----|-----|----|
| 0.03 | 3.12 | 0.19 | 0.01 | 0.01 | 0.02 | 0.47 | 0.08 |

Microtexture of the partially recrystallized specimens was measured using EBSD. All measurements were performed on the cross sections defined by rolling and normal direction. The observed area were electrolytically polished to avoid deformation layer induced by mechanical specimen preparation. The specimens used for EBSD were further measured with X-ray diffractometer. The incomplete \{110\}, \{200\} and \{112\} pole figures were obtained from a Siemens D5000 X-ray diffractometer with Mo radiation for the characterization of global texture. The true orientation distribution function (ODF) was calculated from the four sets of pole figures using serial expansion method[9].

3. Results and discussion

3.1. Nucleation site

The SEM micrographs (Figure 1) show the microstructure in the center of the specimens annealed at 650°C. It was found that the deformed matrix consists of shear bands (SB) and deformed grain boundaries (DGB) which originate from grain boundary before cold rolling. The shear bands are parallel with an angle of about 35° to the rolling direction. In shear bands, there are flat microbands with average separation of 0.2-1μm. The misorientation among microbands is small. The friction between rolls and sheets during cold rolling produces shear stress which induces complex deformation microstructure (Figure 1b)[10]. The structure between shear bands are more like cell blocks which comes from fragment of grains during deformation. Compared with microbands, the curvature of cell blocks with submicron size exhibits dispersion misorientations.
At the onset of recrystallization, there are two kinds of nucleation sites: DGB and SB. Due to high degree of disorder and lots of precipitates, the recrystallized grains such as G1, G3, G4 and G5 preferentially nucleated at DGB. The misorientation of cell blocks is bigger than that of microbands so that the recrystal grains such as G2, G6 –G9 nucleate easily at cell blocks.

3.2. Development of recrystallization texture

After cold rolling, grains of oriented electrical steel sheets tend to locate in some specific orientations e.g. $\alpha$-fiber ($\langle 110\rangle$//rolling direction) and $\gamma$-fiber. The annealing texture is different from that of cold rolling, but the particular relationship exists between recrystallization and cold rolling texture[12]. The $\Phi 2=45^\circ$ sections of ODF of the specimens after annealing at various temperatures are presented in Figure 2. It can be seen that the typical cold rolling texture of ferrite was developed at the center of cold rolled sheets. The strong $\alpha$-fiber texture mainly consists of $\{100\}<110>$, $\{112\}<110>$ and $\{111\}<110>$ components. The intensity of $\{112\}<110>$ component is the strongest. While high intensity of $\{111\}<112>$ component is observed along $\gamma$-fiber. With annealing, the $\gamma$-fiber components
developed while the α-fiber components decreased in their intensities. The texture components between \{111\}<112> and \{111\}<110> exhibit the strongest intensity.

3.3. Microtexture
As seen from the EBSD micrographs of partially recrystallized specimens, the deformed grains mainly belong to the \{111\}<112>, \{111\}<110>, \{112\}<110> and \{100\}<011> components (Figure 3). The deformed grains with different orientations are elongated along the roll direction and distributed alternately. There are narrow shear bands in the deformed grains with the same orientation and substructure with small misorientations is produced. The stored energy and recrystallization rate of deformed grains vary with orientation[13]. The high Taylor factor of γ-fiber components lead to the formation of massive amount of shear bands during cold rolling. The combination of high stored energy and inhomogeneity of dislocation structure plays an important role for the preferential recrystallization at the deformed grains with γ-fiber components. Recrystallization takes place significantly in the deformed grains with \{111\}<112> and \{111\}<110> orientations during the early stage of recrystallization. In contrast, deformed \{112\}<110> and \{001\}<110> grains have low stored energy. Most of the deformed grains with α-fiber components, such as \{112\}<110> and \{001\}<110> components, exist until the middle stage of recrystallization and are replaced by recrystallized grains during the late stage of recrystallization. These observations agree with the results obtained by other researchers[14,15].

![EBSD of partially recrystallized sheets](image.png)

Fig. 3 EBSD of partially recrystallized sheets
(A: 650°C, B: 680°C, C: 710°C, D: 740°C, E: 770°C)

The texture of recrystallized grains is closely related to the texture of deformed grains. The recrystal grains with \{111\}<110> texture component are significantly formed in the deformed matrix with \{111\}<112> component. Besides, they also develop at the boundary between deformed grains with \{112\}<110> component and grains with other components. While the \{111\}<112> recrystallized texture component is formed in the deformed matrix with \{111\}<110> texture component and the boundaries of the deformed grains with \{112\}<110> and \{001\}<110> texture components. A few Goss oriented recrystallized grains are formed and do not contact with each other.

3.4. Microtexture
The orientation relationships between deformed and recrystallizing grains may have a strong effect on the recrystallization process. The high-angle grain boundary exhibits low active energy and high...
migration rate, so the large angle misorientation between recrystallized and deformed grains promotes
the recrystallization. The orientations of 72 recrystallized grains and their surrounded deformed grains
were measured in the specimens annealed at 650°C. The misorientation between recrystallized grains
and the surrounded deformed grains was calculated. The results showed that the misorientation is
between 25° and 45°. So, most of the recrystallized grains are surrounded by high mobile grain
boundaries at the beginning of recrystallization.

At the same time, the distribution of misorientation in specimens changes during recrystallization.
The statistical result of misorientation is presented in Figure 4. At the early stage of recrystallization,
the misorientation distribution inclines to low angle grain boundary. The frequency of 5-10°
misorientation boundaries is obviously higher than other misorientation angles. As the recrystallization
proceeds, the frequency of 5-10° misorientation boundaries decrease while the frequency of 25-55°
misorientation boundaries increase. The frequency of high angle boundaries increase which focus on
the misorientation of 25-35° at the early stage of recrystallization and 45-55° at the later stage of
recrystallization. The misorientation between \{111\}<112> and \{111\}<110> components is 30°. At the
early stage of recrystallization, the \{111\}<110> and \{111\}<112> oriented recrystallized grains form
firstly in the deformed matrix. With the increase of recrystallization degree, the number of
\{112\}<110> and \{001\}<110> recrystallized grains is increased. With the grain boundary migration,
the recrystallized grains grow leading to more and more recrystal grains to contact with each other.
Therefore, the misorientation of grain boundary changes continuously during recrystallization. A
certain proportion of low angle grain boundaries still exist in the completely recrystallized specimen.
The recrystallization texture mainly consists of \{111\}<112>, \{111\}<110> and \{112\}<110>
components.

Fig. 4 Misorientation distribution of recrystal specimens

4. Conclusions
During the primary recrystallization of cold rolled electrical steel with 3%Si, the preferential
nucleation sites are shear bands and deformed grain boundaries. But the inhibitor impedes the growth
of nuclei at deformed grain boundaries and only the nuclei in shear bands develop into dominated
recrystal grains. The recrystallization tend to occur in the deformed grains with \{111\}<112> and
\{111\}<110> texture components because of their high stored energy at the early stage of
recrystallization. The recrystallization texture with intensity maxima at \{111\}<112> and \{111\}<110>
is formed at the beginning and is maintained to the end of the recrystallization. The \{112\}<110> and
\{001\}<110> oriented recrystallized grains developed at the middle stage of recrystallization. The
misorientation between recrystal grains and the surrounded deformed matrix mainly consists of high
angles. The frequency of grain boundaries with misorientation angles of 25-55° increases during
recrystallization. A few Goss grains are formed after recrystallization. But the misorientation between
Goss grains and surrounded grains mainly aggregates in the range of 25-55°.

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