Research Article

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The origin of \{113\}<361> grains and their impact on secondary recrystallization in producing ultra-thin grain-oriented electrical steel

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Abstract: Ultra-thin grain-oriented electrical steel with a thickness of 80 µm is produced by one-step-rolling with industrial grain-oriented electrical steel. The research employs electron back-scattering texture analysis technique to investigate the evolution of deformation and recrystallization textures in this specific steel. Emphasis is placed on examining the origin of \(\{113\}<361>\) grains and their consequential impact on secondary recrystallization. It is revealed that primary, secondary, and tertiary recrystallization phases are integral during the annealing process. The origin of surface \(\{113\}<361>\) grains were result of initial deviated Goss grains with specific shear deformation behavior in cold rolled ultra-thin strips. Additionally, the influence of these grains on texture evolution is predominantly evident during secondary recrystallization. These grains potentially undergo abnormal growth in secondary recrystallization, exploiting high-energy grain boundaries among Goss grains. This phenomenon consequently leads to the diminution of the sharp Goss texture formed during primary recrystallization. Given the magnetic properties and predominant applications of ultra-thin grain-oriented electrical steel in medium-frequency fields, it is recommended to prepare ultra-thin grain-oriented steel during primary recrystallization phase.

Keywords: ultra-thin grain-oriented electrical steel, \(\{113\}<361>\), grains, Goss texture, secondary recrystallization

1 Introduction

Grain-oriented electrical steel is a vital soft magnetic material predominantly used in transformer manufacturing [1]. The global movement toward environmental protection and energy efficiency necessitates the development of transformers with reduced core loss, achievable through the diminution of grain-oriented silicon steel thickness [2,3]. As the thickness of these steel strips lessens, the inhibitors involved hasten decomposition and coarsening during the high-temperature annealing process. This presents a challenge in producing grain-oriented silicon steel sheets with thicknesses under 160 µm through secondary recrystallization with inhibitors [4]. An emerging method to fabricate ultra-thin (less than 100 µm) grain-oriented silicon steel sheets involves using one-step-rolling and recrystallization annealing. Specifically, using grain-oriented silicon steel finished plates as the initial materials, after one-step-rolling and recrystallization annealing, the ultra-thin grain-oriented electrical steel was prepared by means of the heritability of Goss texture. Ishiyama pioneered the production of ultra-thin grain-oriented electrical steel was prepared by means of the heritability of Goss texture. Ishiyama pioneered the production of ultra-thin grain-oriented electrical steel exhibiting exceptional soft magnetic properties in a vacuum furnace by manipulating annealing process [5]. This innovation has since ignited considerable interest in the research and production of ultra-thin grain-oriented electrical steel [6–9].

Gao et al. undertook the preparation of ultra-thin oriented silicon steel utilizing asynchronous rolling, exploring the effects of the rolling method on the texture and magnetic properties of the steel [10]. Meng et al. studied the production process of ultra-thin oriented silicon steel, scrutinizing the formation mechanism of the \(\eta\langle001\rangle\parallel RD\) texture and proposing methods for attaining a strong \(\eta\langle001\rangle\parallel RD\) texture [11]. This provided a theoretical foundation for the production of ultra-thin grain-oriented electrical steel. The texture evolution in producing ultra-thin grain-oriented electrical steel demonstrates heritability. Thus, the cold rolling reduction and initial Goss \((\{110\}<001>)\) orientation sharpness profoundly affects the final product’s properties. Previous investigations

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revealed that when the cold rolling reduction rate is set at 70%, the η ([001] || RD) texture is at its sharpest, exhibiting the most favorable magnetic properties [12]. During the annealing process, the initial sharpness of the Goss texture significantly influences the subsequent texture evolution. Samples with higher initial Goss orientation degrees can achieve a sharper Goss texture in the initial recrystallization through the inheritance of Goss texture, while those with lower initial Goss orientation degrees necessitate secondary recrystallization via surface energy to optimize the texture [13]. Despite advancements in controlling the texture of ultra-thin grain-oriented electrical steel, the consistent appearance of {113} <361> oriented grains, which are detrimental to magnetic properties, remains an unresolved issue. The origin of these grains is yet to be clarified, and there is scarce attention and reporting on the (113)<361> orientation formed in ultra-thin grain-oriented electrical steel.

{113}<361> grains, a variant of the {h,1,1}<1/h,1,2> texture, are traditionally viewed as unfavorable for magnetic properties [14]. These grains mainly originate from the initial {001}<120> texture and may form as island grains, affecting the abnormal growth of Goss grains, as indicated in previous studies [15]. However, silicon steel strips prepared through the one-step-rolling method do not exhibit {113}<361> grains in their initial texture.

Considering the widespread occurrence and unique characteristics of {113}<361> grains in grain-oriented electrical steel, it is imperative to investigate their origins and potential impacts on secondary or tertiary recrystallization in ultra-thin grain-oriented electrical steel. Additionally, the rolling conditions of thin sheets significantly differ from those of conventional rolling, thereby necessitating an in-depth examination of the deformation and recrystallization behaviors of ultra-thin grain-oriented electrical steel.

This article focuses on the production of ultra-thin grain-oriented electrical steel using a one-step-rolling method with industrial grain-oriented electrical steels. The study meticulously examines the deformation and recrystallization texture evolution, with particular attention to the origins of {113}<361> grains and their subsequent effects on secondary recrystallization.

2 Materials and methods

Industrial grain-oriented electrical steels, with a thickness of 0.27 mm and magnetic properties characterized by $B_\text{r} = 1.917 \text{T}$ and $P_{1.5\text{g}} = 1.032 \text{W/kg}$, were cold-rolled to a thickness of 0.08 mm using a rolling machine equipped with 50 mm diameter rolls. The cold-rolling reduction achieved was approximately 70%. The composition of these steels, expressed in mass fraction percentages, is as follows: C 0.003, Si 3.1, Mn 0.17, S 0.007, Al 0.02, N 0.01, and Cu 0.52. The rolling sequence implemented was from 0.27 to 0.12 mm, and finally to 0.08 mm. To enhance the thinning capability and shape control of the four-roll rolling mill in the laboratory, tension rolling was employed. This process involves welding the steel strip’s ends to a tension machine after threading through the mill. Typically, without tension rolling, the unit volume in the deformation zone experiences a three-dimensional compressive stress state. Tension rolling modifies this to a two-dimensional compressive stress coupled with uniaxial tensile stress, thereby reducing deformation resistance and aiding in strip deformation. The structure and texture of the initial samples are presented in Figure 1. The samples exhibit thorough secondary recrystallization with a grain size in the centimeter range, as depicted in Figure 1a. The {200} scatter pole figures indicate that the recrystallization texture of the initial samples is predominantly characterized by Goss texture, with a deviation angle within $10^\circ$, as shown in Figure 1b.

The recrystallization annealing process employed rapid heating under a pure N2 atmosphere (samples were placed in the furnace after reaching respective temperature points), followed by maintenance for 5 min under a pure H2 atmosphere. The schematic of the ultra-thin grain-oriented electrical steel preparation process is illustrated in Figure 2. Annealed samples were extracted at temperatures of 800, 900, 1,000, 1,100, and 1,200°C for texture and microstructure analyses. The micro-textures were measured and analyzed using a Zeiss ULTRASS scanning electron microscope equipped with an Oxford Instruments HKL-Channel 5 EBSD system. The magnetic flux densities at 800 A/m along the rolling direction (RD) and typical iron losses, including $P_{1.0/50}$, $P_{1.0/400}$ and $P_{1.0/1,000}$ ($P_{1.0/50}$ is determined at a magnetic flux density of 1.0 T and

![Figure 1: Structure and texture of initial samples: (a) macrostructure of initial samples and (b) {200} pole figure.](image-url)
50 Hz; the other P values can be deduced by analogy), were measured using an electrical steel tester (MPG 200D).

3 Results and discussion

3.1 Origin of {113}<361> grains in producing ultra-thin grain-oriented electrical steel

Analyzing the samples during cold rolling provides insights into their behavior in the cold-rolled state and lays the groundwork for investigating the origin of {113}<361> grains. Figure 3 displays the imaging maps of cold-rolling and primary recrystallization annealing at 700°C. The cold rolling texture is dominated by γ-{111}<u,v,w> texture after a 70% reduction, as shown in Figure 3a and b. {111}<112> is identified as a typical result of Goss orientation rotating around the transverse direction axis, analogous to Goss single-crystal deformation behaviors [16–19]. Notably, a few {113}<361> grains are observed, as indicated in the green line area of Figure 3b and c. The appearance of {113}<361> grains on the surface, adjacent to deviated Goss grains, suggests that their origin is linked to the initial orientation. Following recrystallization annealing at 700°C, {113}<361> grains remain visible on the surface, as depicted in Figure 3d and e. The consistent presence of grain {113}<361> is not coincidental, it is associated with adjacent Goss grains and surface shear behavior.

The recrystallization texture of {h111}<1/h12> has been documented in prior reports [20], and it is posited that this texture originates from {100}<011> or α<110>∥(RD) fiber in BCC metals subjected to heavy rolling and annealing. However, in this study, α-fiber is not present due to moderate reduction (70%), as shown in Figure 3. Hence, it is hypothesized that the {113}<361> grains observed here do not originate from shear bands in α-fiber, but rather are linked to the initial orientation. The deformation of thin sheets involves
more rolling passes compared to conventional rolling, and
the shear deformation of cold-rolled strips is more
pronounced [21]. As a result, thin strips undergo a distinct
compressive deformation process compared to traditional
cold-rolled sheets, featuring strong surface shearing, which
alters the strain state from plane strain and changes the
crystal rotation route. During ultra-thin strip rolling, when
the thickness reduction leads to the sum of elastic deforma-
tions between the rolling roll and the stand exceeding the
thickness of the rolled piece, negative roll gap rolling occurs,
as illustrated in Figure 4. This condition, under the action of
preloading force, presses the working roll ends together,
forming a loaded roll gap in the roll body’s middle, roughly
equal to the rolled piece’s width and thickness. Consequently,
the edges of the rolled piece are subjected to transverse com-
pressive stress, and the thin strip endures increased shear
force during rolling. The surface deviated Goss grains rotate
along the RD axis to (113)-361> under the shear effect on the
cold-rolled surface of ultra-thin strips.

Zhang et al. [22,23] have previously calculated the
crystal rotations of Goss grains during deformation under
visco-plasitic self consistent models, as shown in Figure 5. It
is believed that (110)-229> grains can rotate to near (114)
\(<u,v,w>\) orientation under surface shear, aligning with the
findings of the (113)-361> component in this study. Analy-
zing the deformation path of (200) pole figures in Figure
3c and the rotation path of Goss orientation under the VPSC
model, both experimental and theoretical research indicate
that the (113)-361> grains result from initial deviated Goss
grains experiencing specific deformation behaviors on the
cold-rolled surface.

3.2 Texture evolution during
recrystallization annealing

The evolution of micro-textures in thin silicon steels is
illustrated in Figure 6. A comprehensive analysis reveals
that the recrystallization texture components primarily
include (110)<001>, (113)<361>, and γ(111)<u,v,w> fiber,
aligning with findings from previous studies [24,25].
During the high-temperature annealing process, pri-
mary, secondary, and tertiary recrystallization occurred, but
with a distinctive change in the secondary recrystallization
components. The primary recrystallization texture, observed
at 850°C, was predominantly composed of Goss texture, sup-
plemented by a minor presence of (113)<361> and γ-fiber, as
indicated in Figure 6a. Upon heating to 850°C, the annealed
samples exhibited the strongest Goss texture, as depicted in
Figure 6b. As the annealing temperature increased, the
strength of the Goss texture diminished, while (113)<361>
showed a notable growth advantage, as presented in
Figure 6c and d. After annealing at 1,200°C for 1 h, the
recrystallization texture primarily consisted of Goss tex-
ture, as shown in Figure 6e.

Figure 7 illustrates the imaging of grain orientation at
various annealing temperatures. During the primary recrys-
tallization stage, the structure was dominated by Goss tex-
tures, reflecting the heredity of these textures. A small num-
er of (111)-112> grains originated from deformed γ grains, and
the (113)<u,v,w> grains resulted from cold rolling, as shown in
the orange grains of Figure 7a. With rising annealing tempera-
tures, the grain size increased, and grain growth became more
dependent on orientation.

It is well known that Goss, (110)-112>, and (210)-001>
are the three types of representative grain orientations
which have the ability to grow abnormally in the grain-
oriented silicon steel [26,27]. However, in this article, we
found that (113)-361> grains, which do not normally have
the ability to grow abnormally under traditional rolling
and annealing process, were able to grow abnormally, an
observation that has not been made in previous research.
When the temperature rose to 950°C, due to the different
growth advantages of grains with different orientations,
the organization becomes uneven, the grain growth rate
of (113)-361> is higher than that of Goss grains, as shown in
Figure 7b. When the temperature rose to 1,050°C, the phe-
nomenon of abnormal grain growth of (113)-361> grains is
more obvious. Since the size of (113)<361> grains is greater than 1 mm, this process belongs to the secondary recrystal-

lization stage, as shown in Figure 7c. In order to deeply analyze the reasons for abnormal growth of (113)<361>
grains, the misorientation distribution of Goss and (113) <361> grain is processed, as shown in Figure 8. It can be

Figure 6: Texture (φ2 = 45° section of ODFs) in different annealing temperatures: (a) 800°C, (b) 900°C, (c) 1,000°C, (d) 1,100°C, and (e) 1,200°C.

Figure 7: Imaging of grain orientation in different annealing temperatures: 850°C, (b) 950°C, (c) 1,050°C, (d) 1,150°C, and (e) 1,200°C.
seen from Figure 8 that although there are small angle grain boundaries between Goss grains, their orientation deviation angle is greater than that of {113} grains.

In the ultra-thin grain-oriented electrical steel process, the deterioration of the Goss texture during secondary recrystallization is primarily due to the texture suppression effect. This means that, compared to other grains, Goss grains have small-angle boundaries, preventing further growth. However, in the traditional recrystallization process of oriented silicon steel, Goss grains grow abnormally due to their size advantage, as Goss grains with small angle grain boundaries can be considered as a large Goss grain [28,29]. As isolated grains, {113}<361> grains are merged by the surrounding Goss grains to complete secondary recrystallization. Therefore, the abnormal growth in ultra-thin grain-oriented silicon steel is not closely related to the texture suppression effect, but rather to the high energy grain boundaries between Goss subgrains. Although these subgrains form low-angle grain boundaries, they cannot be regarded as a single large Goss grain. Compared to {113}<361> grains, Goss subgrains have a larger deviation angle, more crystal defects, and higher grain boundary energy. According to the principle of reducing system energy
(grain boundary energy), \(\{113\}<361>\) grains can abnormally grow by exploiting high-energy grain boundaries between Goss subgrains.

As the annealing temperature increases, the grain size significantly exceeds the sheet thickness, and surface energy becomes the main driving force [30]. The growth rate of Goss grains increases substantially, reducing the size difference between Goss and \(\{113\}<361>\) grains, as shown in Figure 7d. After annealing at 1,200°C, surface-energy-induced tertiary recrystallization, led by specific \(\{110\}\) surface planes, results in a tertiary recrystallization structure dominated by Goss texture, as indicated in Figure 7e.

### 3.3 Magnetic properties

The magnetic properties of ultra-thin grain-oriented electrical steel at different frequencies are presented in Figure 9. As the recrystallization textures were consistently dominated by Goss texture, which contributes positively to magnetic properties, most samples met the JEM1239(GT100) standard [31]. Figure 9a shows that with increasing annealing temperature, the variation in magnetic induction parallels the strength of Goss texture. At 900°C, where the Goss textures reached their peak strength and other texture components, particularly unfavorable \(\{111\}<uvw>\) and \(\{113\}<uvw>\) textures, were weak, the samples exhibited excellent magnetic properties, with \(B_{\text{c50}}\) reaching up to 1.88 T. As the annealing temperature increased to 1,000°C, the intensity of Goss texture decreased significantly, correlating with a decline in the magnetic properties of the annealed samples. Annealing at 1,100 and 1,200°C led to the occurrence of tertiary recrystallization, which correspondingly improved the magnetic properties of the annealed samples.

Changes in iron loss with annealing temperature are depicted in Figure 9b–d. The overall trend in iron loss is characterized by an initial decrease, followed by an increase, and then another decrease. At low frequencies, the iron loss of the samples at all temperatures conformed to the JEM1239 standard. Specifically, at 900°C, the experimental sample exhibited the lowest iron loss, attributed to the strong Goss texture prevalent at this temperature. As the annealing temperature increased, the favorable texture deteriorated, and the microstructure became uneven during the secondary recrystallization process, leading to a gradual increase in iron loss. The lowest iron loss value was observed at 900°C, due to the combined effect of Goss texture sharpness and microstructure homogeneity, as shown in Figure 9b. At medium and high frequencies, the variation trend in iron loss at different temperatures was essentially consistent with the low-frequency variation. Iron loss at annealing temperatures of 800, 900, 1,100, and 1,200°C met the JEM1239 standard, as indicated in Figure 9c and d. It is noteworthy that, compared to medium and low frequencies, the lowest iron loss at high frequencies occurred at 900°C.

Magnetic properties depend on several factors, including sample surface quality, thickness, silicon content, texture, and grain size. The magnetic properties of the samples in this study were closely associated with grain size and texture. Magnetic induction in most samples met the JEM1239(GT100) standard at different annealing temperatures, largely due to the stronger Goss texture and weaker \(\gamma\)-fiber texture. Iron loss is influenced by both texture and grain size. Generally, hysteresis loss predominates at lower frequencies, while eddy current loss becomes more significant at higher frequencies. At low frequencies, iron loss is closely related to the strength of the Goss texture. Owing to the strong Goss texture, the lowest \(P_{1,0/50}\) and \(P_{1,0/400}\) values were recorded at 1,200°C. At high frequencies, the eddy current loss constitutes a larger portion of the total iron loss, making grain size a more influential factor. The smallest \(P_{1,0/1,000}\) value was observed at 900°C, attributable to the strong Goss texture and small grain size after annealing. Considering that ultra-thin grain-oriented steel is primarily used in medium frequency fields and iron loss is a key consideration, it is advisable to prepare ultra-thin grain-oriented steel at primary recrystallization annealing at 900°C.

### 4 Conclusions

This study focused on industrial grain-oriented electrical steel, which was cold-rolled and annealed to explore the texture evolution during deformation and recrystallization of ultra-thin grain-oriented electrical steel. Special emphasis was placed on analyzing the origin of \(\{113\}<361>\) grains and their impact on secondary recrystallization. The origin of surface \(\{113\}<361>\) grains was the result of initial deviated Goss grains with specific shear deformation behavior in cold rolled ultra-thin strips. The influence of \(\{113\}<361>\) grains on texture evolution is predominantly evident during secondary recrystallization. These grains potentially undergo abnormal growth in secondary recrystallization, exploiting high-energy grain boundaries among Goss grains. This phenomenon consequently leads to the diminution of the sharp Goss texture formed during primary recrystallization. Given the magnetic properties and predominant applications of ultra-thin grain-oriented electrical steel in medium-frequency fields, it is recommended to prepare ultra-thin grain-oriented steel during primary recrystallization phase.
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