

Evolution of Columnar Grain Texture in Fe-3%Si Electrical Steel Cast Slabs (Postprint)

Authors: Fu Yongjun, Yang Ping, Jiang Qiwu, Wang Xiaoda, Jin Wenxu

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Abstract

Columnar grains with different quantities having their long axes parallel to the rolling direction in Fe-3%Si electrical steel cast slabs were subjected to cold deformation and recrystallization annealing, and the transformation behavior of columnar grain texture was studied using EBSD analysis. The results indicate that when the original columnar grain was a single grain with cube orientation, single-pass cold rolling with a high reduction ratio and subsequent recrystallization annealing were unfavorable for retention of the cube texture; two-pass cold rolling with a low reduction ratio and recrystallization annealing led to the formation of a strong cube texture, which strongly hindered abnormal growth of Goss grains. When the original columnar grains were dual columnar grains with cube and Goss orientations, under high reduction ratio cold rolling conditions, the Goss orientation rapidly rotated toward $\{111\}\langle 112 \rangle$ while the cube orientation was effectively retained, and no strong interaction existed at the grain boundaries between Goss- and cube-oriented columnar grains. When the original columnar grains were multiple columnar grains with various orientations, the columnar grain boundaries could promote gamma texture and reduce cube texture, thereby facilitating abnormal growth of Goss grains.

Full Text

Evolution of Textures of Columnar Grains in Fe-3%Si Electrical Steel Slabs

FU Yongjun^{1,2}, YANG Ping¹, JIANG Qiwu², WANG Xiaoda², JIN Wenxu²

¹) School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083

²) Cold Rolling Silicon Plant, Anshan Steel Co., Ltd., Anshan 114021

Correspondent: YANG Ping, professor, Tel: (010)82376968, E-mail: yangp@mater.ustb.edu.cn

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Abstract

Different numbers of columnar grains with their major axes parallel to the rolling direction were extracted from Fe-3%Si electrical steel slabs and subjected to cold deformation and recrystallization annealing. The evolution of columnar grain textures was investigated using electron backscatter diffraction (EBSD) analysis. The results show that for a single columnar grain with initial cube orientation, high-reduction primary cold rolling and recrystallization annealing are detrimental to cube texture retention. However, low-reduction secondary cold rolling and recrystallization annealing produce a strong cube texture that strongly inhibits abnormal growth of Goss grains. For samples containing two columnar grains with cube and Goss orientations, high-reduction cold rolling causes the Goss orientation to rotate rapidly toward $\{111\}\langle 112\rangle$, effectively preserving the cube orientation, with no strong interaction across the boundary between Goss and cube-oriented columnar grains. For multi-columnar grains with various orientations, the boundaries between columnar grains promote γ -texture formation and reduce cube texture, which favors abnormal growth of Goss grains.

KEY WORDS columnar grain; Fe-3%Si electrical steel; cold deformation; recrystallization annealing; texture

Electrical steel is an essential soft magnetic alloy in the power, electronics, and military industries. Both grain-oriented and non-oriented silicon steels achieve superior magnetic properties through controlled development of favorable textures. Grain-oriented silicon steel obtains a strong Goss texture by controlling cube and γ -textures [1–4], while non-oriented silicon steel achieves higher contents of $\{100\}$ and $\{110\}$ textures by controlling γ -texture [5–7].

Columnar grains are a common microstructural feature in continuous casting slabs that provide a strong initial cube orientation. Their characteristic high proportion of $\{100\}$ texture benefits the magnetic properties of non-oriented silicon steel [8,9], but can cause surface ridging defects and significant grain size heterogeneity. Strong $\{100\}$ texture also has detrimental effects on Goss texture development in grain-oriented silicon steel [10,11], prompting industry to generally avoid columnar grains. Numerous studies have investigated the

microstructure and properties of columnar grains in electrical steel under various processing conditions, including thin slab casting and rolling technologies [12–15]. The role of grain boundaries when columnar grains are rolled in different directions, the influence of initial columnar grain orientation on recrystallization texture after cold rolling, and the cold rolling and recrystallization behavior of single crystals with cube orientation have been reported [16–20]. However, research on the interactions between different numbers of columnar grains after cold deformation and recrystallization remains relatively limited.

This study selected Fe-3%Si electrical steel slabs containing different numbers of columnar grains with their long axes parallel to the rolling direction as initial material. The evolution of cube-oriented microstructure inheritance and the interaction of grain boundaries on cube and Goss orientations were investigated under conditions without strong surface shear effects from hot rolling deformation and with weak inhibitory forces.

1. Experimental Methods

A 230 mm thick Fe-3%Si (mass fraction) slab was hot-acid etched in 20% HCl solution at 70 °C for 70 minutes. Through macrostructure observation, three types of initial columnar grain structures containing different numbers of columnar grains—single, double, and multi-columnar grains—were identified and sectioned with their major axes parallel to the rolling direction. All samples had a thickness of 3 mm.

The original columnar grain samples were processed to simulate the manufacturing route of grain-oriented silicon steel under laboratory conditions. The processing route and main parameters were: primary cold rolling (82% reduction), recrystallization annealing (820 °C, 4 min), secondary cold rolling (47% reduction), recrystallization annealing (830 °C, 4 min), and secondary recrystallization annealing (1200 °C, 10 h).

A Quanta 400 scanning electron microscope (SEM) equipped with a Hikari EBSD system was used for texture measurement and analysis of the original and processed samples. The columnar grain samples were examined on the transverse section. Cold-rolled and recrystallization-annealed samples were primarily examined on the longitudinal section surface layer; for comparison, the center layer of primary cold-rolled samples was also analyzed. Secondary recrystallization-annealed samples were examined on the rolling plane.

2. Results

2.1 Initial Columnar Grain Orientations

[Figure 1: see original paper] shows EBSD orientation maps and {001} pole figures of the initial columnar grain structures. The single columnar grain exhibited a cube orientation

($\{001\}\langle 100\rangle$). The double columnar grains showed cube and Goss orientations. The multi-columnar grains consisted of cube, Goss, and brass orientations.

2.2 Primary Cold Rolling (82% Reduction)

2.2.1 Cold Deformation Textures [Figure 2: see original paper] presents EBSD orientation maps and $\{001\}$ pole figures of the surface layer after primary cold rolling with 82% reduction. The single columnar grain with cube orientation transformed to $\{001\}\langle 210\rangle$, with the upper and lower regions corresponding to two equivalent variants of $(001)[210]$ and $(001)[120]$, both in high content. In the double columnar grains, the Goss orientation rotated to $\{111\}\langle 112\rangle$, with two equivalent orientations $(111)[112]$ and $(111)[121]$ appearing alternately within the same grain; the $(111)[112]$ content was significantly higher than $(111)[121]$. The cube orientation remained unchanged. The multi-columnar grains transformed to $\{001\}\langle 210\rangle$, cube, and rotated cube orientations belonging to the $\{100\}$ fiber.

Due to the large initial size of columnar grains, the microstructure remained coarse after 82% reduction. To compare orientation differences between surface and center layers after high-reduction cold rolling, the center layers of double and multi-columnar grain samples were analyzed, as shown in [Figure 3: see original paper]. The center and surface layers of double columnar grains showed similar main texture types, as did those of multi-columnar grains, differing only in area fraction. Therefore, surface orientation information can represent the entire sample to some extent.

2.2.2 Recrystallization Annealing Textures [Figure 4: see original paper] shows EBSD orientation maps and ODF sections ($\phi_2=45^\circ$) after cold rolling with 82% reduction and recrystallization annealing. All three samples exhibited low cube texture content and strong $\{113\}\langle 631\rangle$ and $\{113\}\langle 031\rangle$ textures. As the number of original columnar grains increased, the $\{111\}\langle 110\rangle$ orientation content in the annealed texture gradually increased. The average grain diameters decreased progressively: 20.1 μm , 18.7 μm , and 17.7 μm .

2.3 Secondary Cold Rolling (47% Reduction)

2.3.1 Cold Rolling Textures [Figure 5: see original paper] shows EBSD orientation maps and ODF sections ($\phi_2=45^\circ$) after secondary cold rolling with 47% reduction. After secondary cold rolling, the single columnar grain sample contained more deformed grains with cube and Goss orientations. The double columnar grain sample showed strong cube texture, with frequent adjacency of brass and rotated copper-oriented grains. The multi-columnar grain sample exhibited strong cube and $\{111\}\langle 112\rangle$ textures. Compared with [Figure 4: see original paper], the $\{113\}\langle 031\rangle$ texture intensity in the single columnar grain and the $\{113\}\langle 631\rangle$ texture intensity in the double columnar grain decreased, while the $\{113\}\langle 031\rangle$ texture intensity in the multi-columnar grain increased.

2.3.2 Recrystallization Annealing Textures [Figure 6: see original paper] shows EBSD orientation maps and ODF sections ($\phi_2=45^\circ$) after secondary cold rolling with 47% reduction and recrystallization annealing. After low-reduction secondary cold rolling and recrystallization annealing, the single columnar grain sample developed the strongest cube texture with weak other texture components. The double columnar grain sample exhibited strong cube texture and texture components close to Goss orientation, similar to the original two grain orientations. The multi-columnar grain sample showed strong γ -fiber texture with few Goss-oriented grains. Compared with [Figure 5: see original paper], all samples showed decreasing $\{113\}$ texture intensity. The average grain diameters decreased progressively: 16.1 μm , 14.1 μm , and 12.4 μm .

2.4 Secondary Recrystallization Textures [Figure 7: see original paper] shows EBSD orientation maps and $\{001\}$ pole figures after high-temperature annealing. After high-temperature annealing, the single columnar grain sample contained many fine grains, including numerous cube-oriented grains. The double columnar grain sample showed increased numbers of abnormally grown grains with larger average size. The multi-columnar grain sample exhibited further increases in both the number and size of abnormally grown grains. Orientations such as $\{111\}\langle 112\rangle$ and $\{111\}\langle 110\rangle$, which form high-angle boundaries with Goss-oriented grains, essentially disappeared. Compared with [Figure 6: see original paper], all samples showed reduced $\{113\}$ texture intensity.

3. Discussion

3.1 Texture Evolution in Single Columnar Grains [Figure 8: see original paper] shows the variation trend of main orientations in single columnar grains. After primary cold rolling with 82% reduction (stage 2), 35% of the cube orientation was retained, while the remainder rotated 25° and 45° about the ND|| $\langle 001\rangle$ axis to form $\{001\}\langle 210\rangle$ and rotated cube orientations, predominantly transforming to $\{001\}\langle 210\rangle$.

After recrystallization annealing of the high-reduction cold-rolled sample (stage 3), the single columnar grain transformed into a polycrystalline structure with strong $\{113\}\langle 631\rangle$ and $\{113\}\langle 031\rangle$ textures, similar to recrystallization textures in fine columnar grains after cold rolling [17]. The increase in γ -texture and decrease in cube texture indicate that annealing after high-reduction cold rolling is unfavorable for cube texture retention but beneficial for γ -texture formation. A small number of Goss-oriented grains were also observed; the $\{100\}$ orientation only rotates to Goss under large deformation, and the large orientation gradient after high-reduction cold rolling provides conditions for Goss-oriented grain formation after annealing.

After secondary cold rolling with 47% reduction (stage 4), the contents of cube, Goss, and γ -textures changed little. After recrystallization annealing (stage 5),

cube texture increased significantly while $\{113\}$ texture decreased markedly, indicating a good conversion relationship between $\{113\}$ and cube textures.

After secondary recrystallization annealing (stage 6), few abnormally grown Goss-oriented grains were present, and their size was relatively small. Numerous fine grains remained, with main orientations similar to the decarburization annealing texture components. [FIGURE:7a1] shows many cube-oriented grains between abnormally grown Goss-oriented grains and other fine grains, demonstrating that cube-oriented grains strongly hinder Goss-oriented grain growth, resulting in relatively small abnormally grown Goss grains.

In summary, for original single columnar grains with cube orientation, high-reduction primary cold rolling and recrystallization annealing are unfavorable for cube texture retention but beneficial for γ -texture formation. Low-reduction secondary cold rolling and recrystallization annealing produce strong cube texture, which is detrimental to abnormal growth of Goss-oriented grains. The texture transformation in single columnar grains follows two paths: the main path is cube $\rightarrow \{001\}\langle 210\rangle \rightarrow \{113\} \rightarrow$ cube, and the secondary path is cube $\rightarrow \{001\}\langle 210\rangle \rightarrow$ Goss.

3.2 Texture Evolution in Double Columnar Grains [Figure 9: see original paper] shows the variation trend of main orientations in double columnar grains. After high-reduction cold rolling with 82% reduction (stage 2), the Goss orientation rotated to $\{111\}\langle 112\rangle$, consistent with results for single Goss-oriented crystals [21]. The cube orientation was completely preserved due to the presence of Goss orientation, indicating that Goss and cube orientations have little mutual influence on orientation transformation during cold rolling. This is mainly because both soft orientations have orientation factors of 0.82, resulting in weak grain boundary interaction [18]. While the original Goss-oriented grain was continuous, after primary cold rolling the $\{111\}\langle 112\rangle$ grains appeared as discontinuous bands distributed within the soft cube-oriented grains, a transformation process that allowed cube orientation retention.

After recrystallization annealing of the high-reduction cold-rolled sample (stage 3), the strong $\{113\}\langle 631\rangle$ and $\{113\}\langle 031\rangle$ textures indicate that cube texture can transform directly to $\{113\}$ orientation without transitioning through $\{001\}\langle 210\rangle$ under specific conditions. The detection region in [FIGURE:4b1] only involved the cube-oriented region after cold rolling of the double columnar grains; if $\{111\}\langle 112\rangle$ deformed grains were present, strong Goss texture would form after annealing.

Secondary cold rolling with 47% reduction (stage 4) significantly weakened $\{113\}$ texture while strengthening cube texture, showing transformation from $\{113\}$ to cube—a phenomenon not obvious in single columnar grains. No strong γ -fiber texture was observed, indicating that the detection region in [FIGURE:5b1] remained within the original cube-oriented region of the double grains. During low-reduction cold rolling, a rotation relationship existed

between brass and rotated copper orientations. Similar to single columnar grains, recrystallization annealing (stage 5) produced strong cube texture and texture components close to Goss orientation, demonstrating certain heritability of the original Goss orientation in columnar grains.

After secondary recrystallization annealing (stage 6), the double columnar grain sample showed larger abnormally grown Goss-oriented grains and fewer fine grains compared with the single columnar grain sample. However, many small cube-oriented grains remained, indicating that even with inherent Goss orientation advantages, good secondary recrystallization cannot be achieved under conditions of high cube texture content in the recrystallization texture.

For original double columnar grains, the cube texture transformation path is: cube \rightarrow $\{113\}$ \rightarrow cube.

3.3 Texture Evolution in Multi-Columnar Grains [Figure 10: see original paper] shows the variation trend of main orientations in multi-columnar grains. After high-reduction cold rolling with 82% reduction (stage 2), less than 10% of cube orientation was retained, mainly transforming to $\{001\}\langle 210\rangle$ and rotated cube orientations. This suggests that the detection region in [FIGURE:2c1] primarily involved the original cube-oriented grains in the multi-grain structure, but the orientation distribution differed from that in single cube-oriented crystals, indicating that the presence of multiple grain boundaries can significantly alter shear stress distribution during cold rolling and thus change orientation distribution characteristics. Compared with fine columnar grains (RD) in the literature [16], significant differences exist. Fine columnar grains showed weak $\{100\}$ texture but strong $\{111\}\langle 112\rangle$ texture after cold rolling, whereas coarse columnar grains in this work effectively retained $\{100\}$ texture without developing $\{111\}\langle 112\rangle$ texture. The essential difference between fine and coarse columnar grains lies in grain boundary density; fine columnar grains have more grain boundaries with stronger ability to change original cube texture type.

After recrystallization annealing of the high-reduction cold-rolled sample (stage 3), besides strong $\{113\}\langle 631\rangle$ and $\{113\}\langle 031\rangle$ textures, the $\{111\}\langle 110\rangle$ texture component content was significantly higher than in single and double columnar grains, markedly different from recrystallization textures dominated by Goss texture in fine RD columnar grains after cold rolling [17].

After secondary cold rolling with 47% reduction (stage 4), $\{113\}$ texture also transformed to cube texture. Due to the larger number of original columnar grains, the sample after high-reduction cold rolling and recrystallization annealing (stage 5) contained small grains with many grain boundaries and high $\{111\}\langle 110\rangle$ texture intensity, resulting in the strongest $\{111\}\langle 112\rangle$ texture in the secondary cold-rolled sample. After recrystallization annealing, although γ -texture intensity decreased, it strongly hindered cube texture development, resulting in the lowest cube content and favoring abnormal growth of Goss-

oriented grains. Conversely, single and double columnar grains, having fewer original grain boundaries and weaker boundary effects, effectively retained cube texture throughout high-reduction cold rolling, recrystallization annealing, secondary low-reduction cold rolling, and subsequent recrystallization annealing, thereby significantly hindering abnormal growth of Goss-oriented grains.

After secondary recrystallization annealing (stage 6), orientations such as $\{111\}\langle 112\rangle$ and $\{111\}\langle 110\rangle$ that form high-angle boundaries with Goss-oriented grains essentially disappeared, indicating that high grain boundary mobility is one factor enabling abnormal growth of Goss-oriented grains. Additionally, surface energy during high-temperature annealing in hydrogen atmosphere can promote secondary recrystallization [10,11]. Besides Goss-oriented grains, cube-oriented grains remained in the matrix, again demonstrating the strong ability of cube-oriented grains to hinder Goss-oriented grain growth.

For original multi-columnar grains, the cube texture transformation path is: cube $\rightarrow \{001\}\langle 210\rangle \rightarrow \{111\}\langle 110\rangle \rightarrow \{111\}\langle 112\rangle \rightarrow$ Goss.

4. Conclusions

1. For original single columnar grains with cube orientation, high-reduction primary cold rolling and recrystallization annealing are unfavorable for cube texture retention but beneficial for γ -texture formation. Low-reduction secondary cold rolling and recrystallization annealing produce strong cube texture that is detrimental to abnormal growth of Goss-oriented grains. The main cube texture transformation path is: cube $\rightarrow \{001\}\langle 210\rangle \rightarrow \{113\} \rightarrow$ cube.
2. For original double columnar grains with cube and Goss orientations, high-reduction cold rolling causes rapid rotation of Goss-oriented grains to $\{111\}\langle 112\rangle$, effectively preserving cube orientation, with no strong interaction across the boundary between Goss- and cube-oriented columnar grains. The main cube texture transformation path is: cube $\rightarrow \{113\} \rightarrow$ cube.
3. For original multi-columnar grains with various orientations, grain boundaries promote γ -texture and reduce cube texture, favoring abnormal growth of Goss-oriented grains. The main cube texture transformation path is: cube $\rightarrow \{001\}\langle 210\rangle \rightarrow \{111\}\langle 110\rangle \rightarrow \{111\}\langle 112\rangle \rightarrow$ Goss.

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