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EFFECT OF COLD ROLLING PROCESS ON TEXTURE EVOLUTION OF GRADIENT MICROSTRUCTURE IN Fe-3,0 % Si NON-ORIENTED SILICON STEEL

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This study focused on the microstructure evolution of non-oriented Fe-3,0 %Si steel used in the core of new energy vehicle drive motor. An hot band and a sample normalized at 800 °C for 10 min were subjected to a moderate cold rolling and an annealing treatment. The results show that the initial hot band has gradient microstructure. After normalizing, the surface is consisted of fine recrystallized grains, the central layer has elongated α-fiber and γ-fiber grains, the subsurface shows a mixed grain structure with strong Goss texture. After cold rolling with a thickness reduction of 40 %, α-fiber and γ-fiber textures are strengthened, and unstable Goss texture disappears. After annealing at 700 °C for 5 min, gradient recrystallization occurs and γ-fiber texture is weakened. The central and subsurface layers show frequently nucleation phenomena in the grain interior and grain boundaries, resulting in strong θ-fiber, α*-fiber and Goss components.

Key words: Fe-3,0 % Si steel, moderate cold rolling, gradient microstructure, annealing, recrystallization behavior

INTRODUCTION

Non-oriented silicon steel is an important Fe-Si binary soft magnetic alloy, which is widely used in drive motors and induction equipment, and has good magnetic properties.

At present, the researches on the cold rolling treatment of non-oriented silicon steel hot band mainly focus on the microstructure evolution [1], while rarely pay attention to the recrystallization behavior of the hot band with gradient micro-structure during cold rolling. Gradient structure can improve the plastic processing performance of silicon steel during cold rolling [2].

In this work, Fe-3,0 %Si non-oriented silicon steel hot rolled band is normalized, cold rolled and annealed. The purpose is to explore the evolution of gradient structure and texture, analyze the recrystallization mechanism during annealing, and provide basic theoretical support for the regulation of microstructure and properties of non-oriented silicon steel after annealing.

EXPERIMENTAL MATERIALS AND METHODS

The raw material used in this experiment is Fe-3,0 %Si non-oriented silicon steel hot band with a thickness of 2 mm. The three-phase ZDXS5 box furnace was used to normalize the hot band at a temperature of 800 °C. The holding time was 10 min, and the cooling method was air cooling. A hot band sample and a normalized sample were cold rolled to 1.2 mm with a medium thickness reduction of 40%, and then annealed at 700 °C for 5 min. Finally, the metallographic analysis was carried out in each stage of normalization, cold rolling and annealing. The microstructure and grain orientation data in the RD-ND sections (RD is the rolling direction, ND is the normal direction) were tested in a ZEISS GeminiSEM 300 field emission scanning electron microscope equipped with an electron backscatter diffraction (EBSD) system. The OIM software was used for data post-processing. The orientation distribution functions (ODFs) were calculated by the series expansion method (L_{max}=22), and the φ_2=45° cross section was shown based on the Bunge system.

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EXPERIMENTAL RESULTS AND ANALYSIS

Microstructure and texture of initial hot band and normalized band

The microstructure of the Fe-3,0 %Si non-oriented silicon steel hot band has a gradient structure along the surface, subsurface and central layers, as shown in the IPF map (inverse pole figure) in Figure 1a. The dynamic recry-stallization behavior occurs at the surface. The surface microstructure is homogeneous and consist of fine recrystallized grains. The central layer is mainly composed of elongated grains, and the subsurface layer shows more elongated grains and a small amount of equiaxed grains.

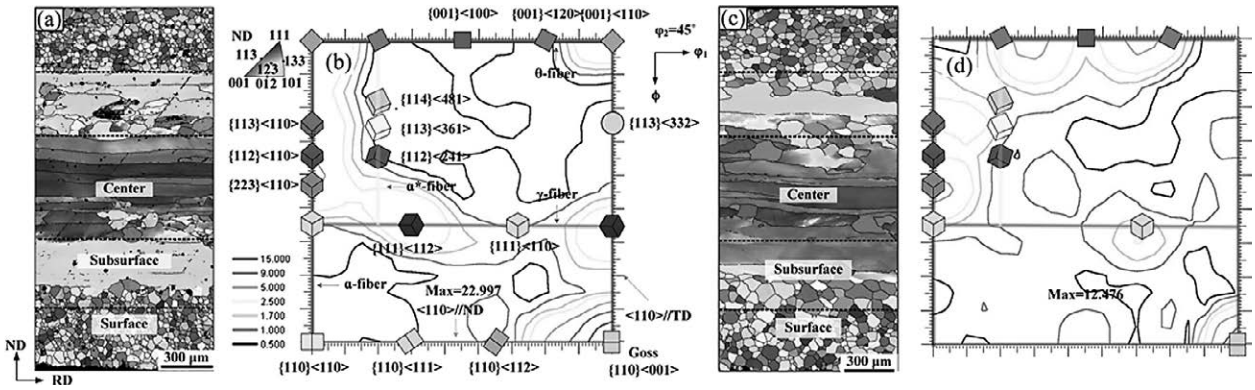

Figure 1 Microstructure (IPF-ND) and texture (φ_2=45°ODF section) of the initial hot band with different normalized treatment. (a, b) initial hot band; (c, d) hot band normalized at 800 °C for 10 min.

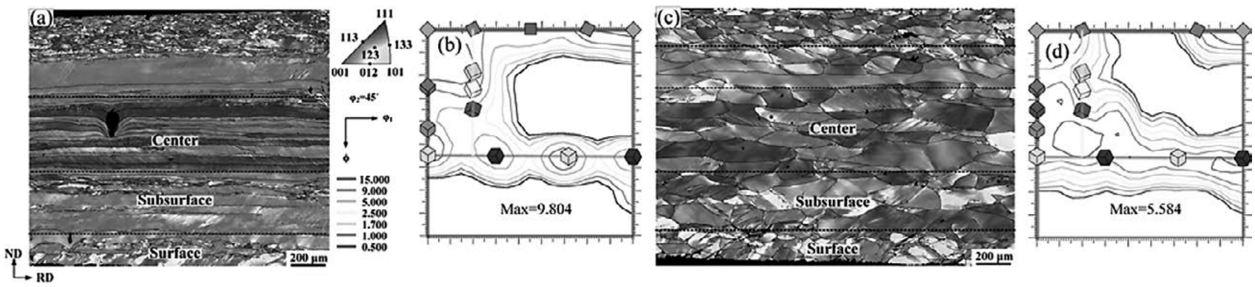

Figure 2 Microstructure (IPF-ND) and texture (φ_2=45°ODF section) of the cold rolled sheets originated from (a, b) initial hot band and (c, d) hot band normalized at 800 °C for 10 min.

As shown in Figure 1b, the hot rolling texture is mainly composed of γ-fiber, α-fiber and Goss components. The Goss texture intensity is the highest, reaching 22,997. The subsurface temperature in the hot band is high and the heat dissipation is slow, leading to a recovery microstructure dominated by a strong Goss texture. The central layer has the smallest shear stress and is dominated by plane deformation. Because of its slow heat dissipation, elongated deformed grains with γ-fiber and α-fiber orientation form in the central region of hot band.

The microstructure of the normalized band is shown in Figure 1c. After normalization treatment, recrystallization behavior occurs. The equiaxed grains in the surface layer grow up. In the subsurface layer, some grains nucleate in the deformed Goss grains. In the central layer, a large number of elongated grains are retained and a small amount of new grain nucleation occurs.

The texture of the sample after normalizing at 800 °C is shown in Figure 1d. The overall texture is significantly weakened. The α-fiber and Goss component are still the dominant recrystallized textures. In addition, a strong θ-fiber and a weak {111}<110> recrystallization texture form.

Microstructure and texture after cold rolling

Figure 2a and 2c show the microstructure after cold rolling. It is seen that the deformed and elongated grains appear along the whole thickness direction. As shown in Figure 2a, after the cold rolling of the initial hot band, the fine deformed grans at surface have greatly various sizes. The subsurface and the central layers are composed of coarse and elongated grains. Thus, the cold rolled microstructure is distributed in a gradient structure. As shown in Figure 2c, due to grain growth appearing in the normalized band, the deformed grains after cold rolling also exhibit large sizes.

The corresponding cold rolled textures of different band is shown in Figure 2b and 2d. During the cold rolling process, crystal orientation changes due to dislocation slip. The cold rolling textures are mainly composed of θ-fiber, α-fiber and γ-fiber components. Compared with initial hot rolled band and normalized band, the α-fiber and γ-fiber textures are more concentrated, and unstable Goss texture disappears. This change of texture components is in accordance with the typical cold rolling texture evolution in Fe-Si steels. It is noted that the {001}<100> (Cube) texture in the cold rolled sheet of initial hot band is stronger than the sheet with normalized treatment.

Microstructure and texture after annealing

The microstructure of the annealed sheets is shown in Figure 3a and 3c. As illustrated in the sample without normalized treatment (Figure 3a), The surface layer is completely recrystallized, and has homogeneously distributed small grains. In the central and the subsurface layers, recrystallization phenomena frequently occur within grains and along grain boundaries. Compared with the sample without normalized treatment, the re-

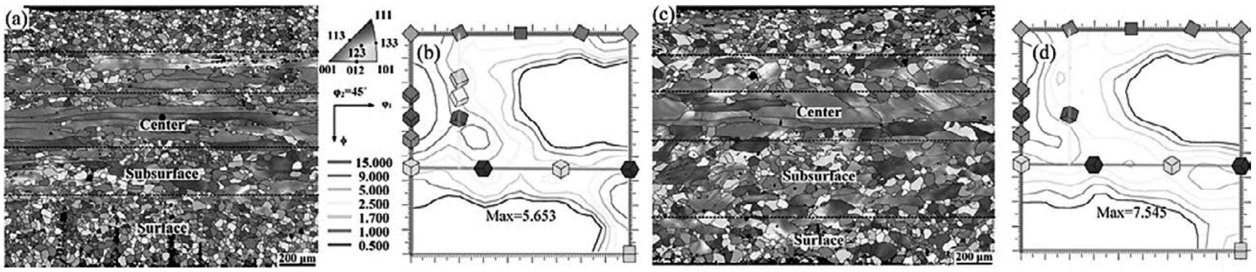

Figure 3 Microstructure (IPF-ND) and texture (φ_2=45°ODF section) of the cold rolled sheets annealed at 700 °C for 5 min originated from (a, b) initial hot band and (c, d) hot band normalized at 800 °C for 10 min.

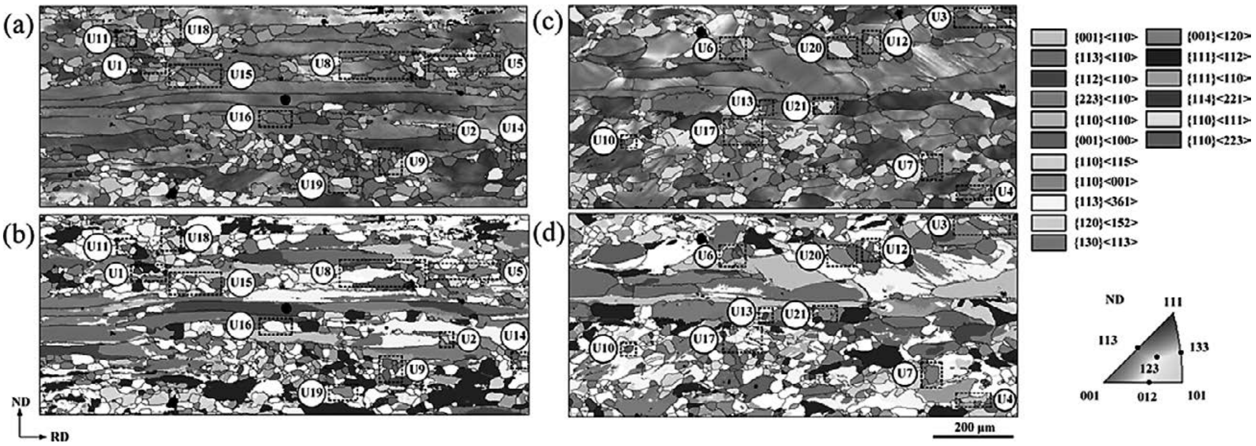

Figure 4 Microstructure (IPF-ND) and grain orientation map in central layer of the annealed sheets originated from (a, b) initial hot band and (c, d) hot band normalized at 800 °C for 10 min.

crystallized grains in the sample with normalized treatment has larger sizes (Figure 3c).

The annealed textures are shown in Figure 3b and 3d. After annealing process, the textures are mainly composed of θ-fiber, α-fiber and γ-fiber components. Compared with the cold rolled sheets, the γ-fiber texture is apparently weakened and the component distribution become random. It is noted that Goss texture reappears in both samples. As reported in the study of Wang Y. [3], the coarse initial microstructure can lead to a large number of nucleation of Goss grains at the shear band and grain boundaries.

RECRYSTALLIZATION BEHAVIOR OF THE CENTRAL REGION DURING ANNEALING

Different to the surface layers, the coarse and elongated central layer grains undergo incomplete recrystallization after annealing at 700 °C for 5 min. The grains with different orientations exhibit diverse nucleation behaviors, as shown in Figure 4. The new grains nucleate at the grain boundaries and shear bands of the γ-oriented deformed matrices. The typical recrystallized grains have Goss, α-fiber, α*-fiber, and θ-fiber orientations.

(1) Recrystallization behavior of θ-fiber grains ({001}<110>, {001}<120> and Cube grains)

The {001}<110> grains mainly nucleate at the boundaries between {111}<112> and {130} <113> matrix grains (U1), and originate from the boundaries between {223}<110> and {113}<361> matrix grains (U2 and U3), and also come from the {111}<110> matrix grain boundaries (U4). As shown in U5, U6 and U7, {001}<120> grains nucleate and grow in the {113} <361> deformed matrix grains, and also originate from the boundaries between {001}<110> and {113}<110> matrix grains. Similar to the {001}<110> grains, Cube grains nucleate at the boundaries between {113}<361> and {113}<110> deformed matrix grains (U8), and also come from the {223}<110> matrix grain boundaries (U9). As illustrated in U10 region, a Cube grain nucleate near the boundaries between {113}<361> and {223}<110> matrix grains.

(2) Recrystallization behavior of α-fiber grains ({113}<110>, {112}<110>, {223}<110> grains)

The {113}<110> grains nucleate at the boundaries of {113}<361> matrix grains (U11), and the boundaries between {001}<110> and γ-fiber matrix grains (U12). Similarly, {112}<110> grains prefer to nucleate at the boundaries between α*-fiber and γ-fiber grains (U1, U13). {223}<110> grains originate from the {113}<361> and {001}<110> matrix grains boundaries (U14).

(3) Recrystallization behavior of α*-fiber grains ({113}<361> grains)

As shown in U5, U15 and U16 regions, several {113}<361> grains nucleate in the {001}<110> and {113}<110> deformed grains. In U17 region, two

{113}<361> grains nucleate in the {111}<112> deformed matrix grains.

(4) Recrystallization behavior of Goss grains

It is observed that Goss grains nucleate at the boundaries between the {120}<152>, {111} <112> deformed matrix grains (U18, U19). In addition, the recrystallization of Goss grains also occurs at the {001}<100> deformed grain boundaries (U20). In U21 region, Goss grains nucleate between {223}<110>, {001}<110> matrix grain boundaries.

In summary, after a moderate cold rolling and annealing, {001}<110>, {001}<120> and Cube grains mainly nucleate at the boundaries of {111}<110>, {111}<112>, {113}<361> matrix grains. A large number of α*-fiber ({113}<361>) oriented grains nucleate at the boundaries of {111}<112>, {001}<110>, {113}<110> matrix grains. Similarly, Goss grains nucleate in {111}<112>, {001}<110>, {223}<110> matrix grains. Combined with the cold rolled and annealed textures, these grains have growth advantages after nucleation, resulting in strong θ-fiber, α*-fiber and Goss components.

CONCLUSION

The microstructure of initial hot band has gradient distribution. After normalizing, The surface is homogeneous and consisted of fine recrystallized grains, the central layer has elongated grains with α-fiber and γ-fiber textures, the subsurface shows a mixed grain structure with strong Goss texture.

After the cold rolling with a moderate thickness reduction of 40 %, α-fiber and γ-fiber textures are more concentrated, and unstable Goss texture disappears, which is in accordance with the typical cold rolling texture evolution in Fe-Si steels.

After annealing at 700 °C for 5 min, gradient recrystallization occurs. The surface layer is completely recrystallized and form homo-geneously small grains. The central and subsurface layers show frequently nucleation phenomena within grains and along grain boundaries, resulting in strong θ-fiber, α*-fiber and Goss components.

Acknowledgments

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Note: The responsible translator for English language is C. Xu, Ningbo, China