{411}<148> Texture in Thin-Gauge Grain-Oriented Silicon Steel

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Abstract The significant occupancy of {411}<148> texture exists in the thin-gauge grain-oriented silicon steel (TG-CRGO is defined that thickness of the sheet is <0.25 mm and the reduction in cold rolling is more than 90%) which has been considered to have obviously effects on the abnormal growth of Goss-oriented grains during the secondary recrystallization process. The microstructures of the TG-CRGO were investigated by X-ray diffraction and electron back-scattered diffraction in this study. It was found that {411}<148> texture mainly exists in the center layer of hot-rolled as well as normalized plates. With the increase in cold rolling reduction, {411}<148> orientation gradually rotates to α -fiber texture (<110>//RD). Finally, few {411}<148> would retain at the boundaries of deformed α -fiber grains (<110>//RD) as the reduction in cold rolling reaches 90%. After annealing treatment, a small amount of γ -fiber textures (<111>//ND) preferably nucleates and recrystallizes between the DBs (deformation bands) at first; then, the {411}<148> recrystallization texture occurs and mainly nucleates at the grains boundaries of the deformed α -fiber grains, and also quite a few {411}<148> orientation grains nucleate in the inner of {112}<110> grains. But this phenomenon was not observed in the {100}<011> deformation grains. With respect to the occurrence of {411}<148> recrystallization texture, it is mainly induced by strong α -fiber as well as weak γ -fiber textures formed during cold rolling other than originating from {411}<148> regions in hot bands.

KEY WORDS: Thin-gauge grain-oriented silicon steel (TG-CRGO); {411}<148> texture; α -Fiber texture; Recrystallization; Electron back-scattered diffraction (EBSD)

1 Introduction

The texture evolution during metal rolling is mainly controlled by the composition of alloy and the parameters of

hot rolling, cold rolling and annealing. A lot of {411}<148> and {311}<136> textures form after recrystallization for the BCC metals with heavy rolling reduction. The origin of {411}<148> texture had been researched in the related single-crystal experiments, and misorientation between nucleation site of {411}<148> grain and original grain had been obtained. Homma et al. [1] studied that very sharp {411}<148> textures were found at the grain boundaries even if the {100}<011> single crystal can hardly recrystallize after heavy rolling reduction. The similar phenomenon was also found in IF steel. Quadir and Duggan [2] found that the {411}<148> texture appeared near {100}<110> cold-rolled texture after annealing treatment of IF steel with 95% of rolling reduction. They considered that the appearance of {411}<148> texture was related to α -fiber deformation band. However, the

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composition of grain-oriented silicon steel was quite different from those of single crystal and IF steel. The difference in alloy system has different effect on deformation and recrystallization textures. What is more, sharp Goss texture needs to be acquired in grain-oriented silicon steel to obtain excellent magnetic properties after a series of complex process. The orientation deviation angle after primary recrystallization, the grain boundary distribution characteristics of Goss texture [3–5] and the size distribution of inhibitor [6] would play an important role in growing process of Goss grain during the secondary recrystallization. Quadir *et al.* [7] found that $\{111\}\langle 112 \rangle$, $\{411\}\langle 148 \rangle$ textures both presented a $\Sigma 9$ relationships, which would benefit the growing of Goss grain. This means that the $\{411\}\langle 148 \rangle$ texture is also conducive to the follow-up process of Goss growing up during secondary recrystallization. Therefore, the $\{411\}\langle 148 \rangle$ texture gains increase attention in the production process of grain-oriented silicon steel. Ushigami *et al.* [8] found that the $\{411\}\langle 148 \rangle$ texture promoted primary recrystallization when the cold rolling reduction increased. Park *et al.* [9] adopted aging treatment during the cold rolling process, which made $\{411\}\langle 148 \rangle$, $\{111\}\langle 112 \rangle$ textures significantly increase after recrystallization. There were a lot of studies about $\{411\}\langle 148 \rangle$ texture in the grain-oriented silicon steel so far. However, the studies about $\{411\}\langle 148 \rangle$ texture distribution characteristics in original hot-rolled plate, the deformation in the process of cold rolling, recrystallization in the annealing process and grain distribution after recrystallization have not been reported.

In this paper, the experimental raw material was the low-temperature hot-rolled grain-oriented silicon steel, which was prepared by one-step cold rolling method. The $\{411\}\langle 148 \rangle$ texture in hot-rolled plate was analyzed. Deformation and recrystallization processes during cold rolling and annealing process were observed, and its evolution mechanism was discussed also.

2 Experimental

The samples used in this work were 2.3-mm-thick Fe–3% Si low-temperature hot-rolled grain-oriented silicon steel plate and the main chemical compositions (mass fraction, %) were C: 0.055–0.060, Si: 3.15–3.20, Mn: 0.10, S: 0.007–0.008, Al: 0.025–0.027, N: 0.0065–0.0070, Sn: 0.03. After normalizing process, the silicon steel sheet was rolled to 0.23 mm by a method of less pass and heavy rolling reduction. The final samples (90% reduction) were treated by different annealing time of 15, 20, 25, 30, 35 and 40 s, respectively. The hot-rolled plate and normalized plate samples were selected as the raw material. Distribution characteristics of $\{411\}\langle 148 \rangle$ texture of hot rolling normalized plates were analyzed. The

samples with a 60% cold rolling reduction were selected and intercepted during cold rolling process, and the final cold rolling samples with a 90% reduction were used to analyze the change in $\{411\}\langle 148 \rangle$ texture in cold rolling process. The samples with different annealing time were chosen to analyze the change in $\{411\}\langle 148 \rangle$ texture in recrystallization process. The samples were cut into a size of 5 mm (TD) $\times$ 10 mm (RD), then polished and corroded on the side face (RD–ND) of the samples. The texture analysis was carried out by electron back-scattered diffraction (EBSD, HKL Company). Besides, macro-textures of the cold-rolled and complete recrystallization samples were measured with a Bruker D8 Advance X-ray diffractometer.

3 Results

3.1 $\{411\}\langle 148 \rangle$ Texture Occurrence of the Hot-Rolled, Normalized and Cold-Rolled Plates

Figure 1 shows EBSD orientation maps of the hot-rolled and cold-rolled samples with different rolling reductions. Figure 1a shows that the texture of the hot-rolled plate existed gradient from the surface upper to center lower layers. The dynamic recovery and recrystallization occurred easily since the surface and subsurface suffered from a large shear force during the hot rolling process. Therefore, on the surface and in the subsurface, apparent recrystallization structures occurred, including typical shear texture [10]. However, the center layer was only subjected to the compressive stress. The recovery structure in the center layer appeared, such as $\{100\}\langle 011 \rangle$, $\{112\}\langle 110 \rangle$, $\{411\}\langle 148 \rangle$ textures. Figure 2 shows the volume fraction of each orientated grain in original structure, which are about 14.6% for $\{112\}\langle 110 \rangle$, about 14.4% for $\{100\}\langle 011 \rangle$ and about 11.1% for $\{411\}\langle 148 \rangle$. Besides the numbers of recrystallization, $\{411\}\langle 148 \rangle$ orientations were obviously more than those of $\{112\}\langle 110 \rangle$ and $\{100\}\langle 011 \rangle$ orientations. As shown in Fig. 1b, the texture distribution had no significant change and was similar to that of hot-rolled plate after the two-pass normalizing process. But the microstructure had changed obviously; the closer to the center layer, the sizes of the grains were larger. Some of them were more than 200 μm . During the cold rolling, the $\{411\}\langle 148 \rangle$ texture in the center layer also decreased significantly and gradually rotated to α -fiber orientation. From Fig. 1c, we could see the obvious local shear deformation occurs in the coarse grain in the center layer, but not on the surface and in the subsurface because the large sizes of the grains lead to the formation of shear band [11]. Figure 1d shows that when reduction ratio reached 90%, the cold-rolled deformed microstructure consisted of alternating long strip α -fiber orientation

Fig. 1 EBSD orientation images of the specimens: **a** hot-rolled plate, **b** normalized plate, **c** cold rolling plate with 60% reduction, **d** cold rolling plate with 90% reduction

Fig. 2 Proportions of different oriented grains in hot-rolled plate

deformation and fragmentation structure with large deformation. Only a small amount of {411}<148> orientation existed in deformation zone. As the rolling reduction increased, the change in the texture gradient on the surface, the subsurface and the center layer became less. Eventually, the textures in each area became similar, and they mainly consist of strong α -fiber textures.

3.2 {411}<148> Recrystallization Texture in Annealing Process

The characteristics of the texture in the annealing process were observed by EBSD. Figure 3 shows the EBSD orientation images of the specimens after different annealing

time. When the cold-rolled plate was annealed for 15 s, the recovery structures were dominant, and recrystallization nuclei were not obvious. When the cold-rolled plate was annealed for 20 s, plentiful recrystallization nucleation sites appeared as the fragmented structures between the banded structures. Since most banded structures were {100}<011> and {112}<110> orientations with low storage energy, recrystallization could hardly happen. With extension of annealing time, the proportion of recrystallization would rise. Figure 3 clearly shows that {411}<148> texture increased gradually, and its proportion raised from 7.87% to 14.3%. When the annealing time reached 40 s, the proportion of recrystallization was above 95%, and very a few banded structures of α -fiber orientation existed. Goss orientation grains took up a very low proportion after recrystallization and mainly distributed in near the surface layer.

4 Discussion

When the alloying components of oriented silicon steel remained unchanged, the cold-rolled texture was mainly affected by the original hot-rolled plate texture and cold rolling reduction. Owing to the motion of slip and accumulation of dislocation in the cold rolling process, the rotation of crystal orientation would occur. Generally speaking, if a certain orientation was near an orientation with stable rolling before cold rolling deformation, it would not deviate from the nearby stable orientation after cold rolling; {112}<110> and {100}<011> were typical

Fig. 3 EBSD orientation images of the specimens after different annealing time: **a** 15 s, **b** 20 s, **c** 25 s, **d** 30 s, **e** 35 s, **f** 40 s

stable orientations and metastable orientations [12]. According to Fig. 4, $\{411\}\langle 148 \rangle$ might rotate to $\{100\}\langle 011 \rangle$ orientation along $\langle 110 \rangle$ axis in the rolling process, or it could also directly rotate to $\{112\}\langle 110 \rangle$ orientation. In plane strain deformation, $\{112\}\langle 110 \rangle$ orientation was considered as the most stable orientation. Under the deformation condition of heavy rolling reduction, stable $\{100\}\langle 011 \rangle$ would be changed into unstable orientation and rotated to $\{112\}\langle 110 \rangle$ [13]. Strong $\{112\}\langle 110 \rangle$ texture would be gained after 90% cold rolling deformation. In the process of cold rolling process, local deformation happened in some large-size grains. As shown in Fig. 5, $\{112\}\langle 110 \rangle$ orientation was dominant, and meanwhile, a small number of $\{411\}\langle 148 \rangle$ orientations existed also. However, such a phenomenon was not observed in $\{100\}\langle 011 \rangle$ grains, which might be caused by characteristic of $\{100\}\langle 011 \rangle$ itself. According to Toge *et al.* [14], two slip systems in $\{100\}\langle 011 \rangle$ crystal had very high space

symmetry and the same Schmid factor; the deformation structure was uniform; and no local stress region existed.

The formation mechanisms of different types of primary recrystallization textures were different. Generally, shear bands were usually considered as the preferentially nucleation sites in subsequently annealing due to higher stored energy. It is considered that Goss grains tended to be formed inside $\{111\}\langle 112 \rangle$ orientation shear bands during annealing [15, 16]. In this study, it was found that only a few Goss grains distributed in the surface layer after annealing, which was related to the distribution of Goss texture in original hot-rolled plate and most Goss texture in primary recrystallization structure would be gained from inheritance of hot-rolled plate [17, 18]. At the preliminary recovery stage of annealing treatment, subgrains would form due to dislocation rearrangement, and therefore, the dislocation density reduced, but the overall texture did not change. Different grains have different recovery speeds. According to Every

Fig. 4 EBSD orientation image and {200} pole figure of the cold-rolled specimens with reduction of 50%: **a** orientation distribution map, **b** {200} pole figure

Fig. 5 EBSD orientation image of {112}<110> grain interior during cold rolling: **a** orientation distribution map, **b** {200} pole figure

and Hatherly [19], {110} and {111} of high storage energy possessed a quicker recovery process than {112} and {100} of low storage energy. According to EBSD results of recrystallization in microarea and corresponding ODF

(orientation distribution Function) maps in Fig. 6, it could be observed that a few recrystallization nucleation sites appeared in the large-deformation structures between long-stripe α -fiber texture deformation bands (DBs) at the preliminary stage of recrystallization. {111}<112> recrystallized structures were dominant; some {111}<110> orientation also existed; and there were few deformed structures of {100}<011> and {411}<148> orientation. As {111}<112> orientation belongs to γ -grains and the storage energy of γ -grains after deformation was higher than α -grains, the {111}<112> orientation would have priority to nucleate during annealing. It was considered that oriented nucleation and growth theory could explain the formation of

Fig. 6 Observation of partially recrystallized texture: **a** early stage of recrystallization, **b** ODF of deformation band ($\varphi_2 = 45^\circ$), **c** ODF of recrystallization texture ($\varphi_2 = 45^\circ$), **d** ODF of deformation band ($\varphi_2 = 45^\circ$), **e** late stage of recrystallization

Fig. 7 Macro-textures of recrystallized specimens in different areas: **a** surface, **b** subsurface, **c** center

Fig. 8 Macro-textures of cold-rolled specimens in different areas: **a** surface, **b** subsurface, **c** center

$\{111\}\langle 112 \rangle$ oriented grain; it presented a relationship of $30^\circ\langle 110 \rangle$ orientation with $\{111\}\langle 110 \rangle$ and a relationship of $35^\circ\langle 110 \rangle$ orientation with $\{112\}\langle 110 \rangle$ [20]. In the later period of recrystallization, plentiful $\{411\}\langle 148 \rangle$ grains began to nucleate, mainly concentrating on the grain boundaries of $\{112\}\langle 110 \rangle$ grains. Meanwhile, a few recrystallization nucleation of $\{411\}\langle 148 \rangle$ orientation can also be found inside the deformed grains of $\{112\}\langle 110 \rangle$. Beck [21] pointed out that crystal nuclei of various orientations existed in the deformed matrix, but only some of them were appropriate to grain boundary mobility, and thus, the growing speed was high for recrystallized texture, where the growth of other crystal nuclei was inhibited. $\{411\}\langle 148 \rangle$ orientation had a large angles with $\{100\}\langle 011 \rangle$ and $\{112\}\langle 110 \rangle$ orientations, which were easy to migrate, and therefore, $\{411\}\langle 148 \rangle$ orientation nucleus could grow into the deformed matrix easily, and strong $\{411\}\langle 148 \rangle$ texture would form. Verbeken and

Kestens [22] also explained the recrystallization behavior of α -fiber orientation structure under large deformation in bcc metals according to oriented growth theory. $\{113\}\langle 471 \rangle$ which is similar to $\{411\}\langle 148 \rangle$, presented a relationship of $19.7^\circ\langle 110 \rangle$ (close to $26.5^\circ\langle 110 \rangle$) with $\{112\}\langle 110 \rangle$.

The traditional Hi-B steel would present strong $\{111\}\langle 112 \rangle$ texture after cold rolling at the reduction of 87% and annealing treatment [23]. Compared with the primary recrystallized texture of traditional Hi-B steel, the recrystallized texture after cold rolling of low-temperature plate with a heavy rolling reduction and annealing was obviously different as shown in Fig. 7, indicating that macro-textures in different regions after recrystallization, textures of the surface layer, subsurface layer and central layer were almost the same after completely recrystallization, and dominated by three textures of $\{411\}\langle 148 \rangle$, $\{111\}\langle 112 \rangle$ and $\{100\}\langle 025 \rangle$. According to the statistical analysis of the specimens after completely recrystallization, it suggests that

the proportion of $\{411\}<148>$ texture reaches 30%, while $\{111\}<112>$ texture only about 15%. According to Fig. 1a, the $\{411\}<148>$ texture mainly distributed in the central layer prior to cold rolling, while the intensity of $\{411\}<148>$ texture was almost equal in these regions after recrystallization, and they were no obvious difference. Therefore, $\{411\}<148>$ texture formed after recrystallization did not only rely on the structure in the initial hot-rolled plate. As shown in Fig. 8, it depends on strong α -fiber texture formed after large-deformation cold rolling. Figure 8 shows the macro-textures after cold rolling of 90% reduction. The surface layer, subsurface layer and central layer were all dominated by α -fiber texture, while γ -fiber texture was weak. As a result, $\{411\}<148>$ ($\{h11\}<1/h,1,2>$) occupied the main part of all textures after annealing, while there were few components of $\{111\}<112>$ texture. According to the comparison analysis between Figs. 7 and 8, cold-rolled textures and recrystallized texture in various regions presented an obvious corresponding relationship.

5 Conclusions

1. For low-temperature grain-oriented silicon steel hot-rolled plate, original $\{411\}<148>$ texture mainly existed in the central layer of the plate. With the increase in cold rolling reduction, the proportion of $\{411\}<148>$ texture reduced. Finally, a few $\{411\}<148>$ grains existed at the grain boundaries of deformed α -fiber grains.
2. During the annealing, abundant recrystallization nucleation sites of $\{411\}<148>$ orientation appeared at the grain boundaries of α -fiber texture. Meanwhile, a few of $\{411\}<148>$ nucleation could also be found inside the $\{112\}<110>$ deformed grains. However, there was no such a phenomenon inside the $\{100\}<011>$ grains to occur.
3. With respect to the occurrence of $\{411\}<148>$ recrystallization texture, it is mainly induced by strong

α -fiber and weak γ -fiber textures formed during cold rolling other than originating from $\{411\}<148>$ regions in hot bands.

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