Change of Rotated Cube Texture through Multi-processing in 3% Si-steels

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Rotated cube texture was obtained about 5% during the 1st heavy cold rolling 80% and the subsequent annealing increased it by 40% but thereafter both the 2nd light cold rolling 10% and the 2nd low temperature annealing at 700°C were not able to increase the rotated cube orientation. This result assures that a small amount of reduction grows hardly the rotated cube orientation and even subsequent annealing of such lightly cold rolled materials does not increase it properly either. The γ fiber of hard magnetizing orientation revealed a large volume fraction above 20% through the 1st cold rolling and subsequent annealing, but it decreased noticeably after the 2nd cold rolling and annealing, which also means that it does not change under such low cold reduction and low temperature annealing. The CSL boundaries of \( \Sigma 3, \Sigma 7, \Sigma 9 \) and \( \Sigma 15 \) appeared as the main \( \Sigma \) boundaries.

KEY WORDS: rotated cube texture; cube texture; γ fiber; CSL boundary.

1. Introduction

In bcc structure the (100) directions are known as easy magnetizing axes and thus the cube texture of \( (001)[100] \) reveals the best magnetic properties. The electrical steels have anisotropy of magnetic properties according to the directions from the rolling direction. However, the cube texture is not obtainable in a large volume from the industrial manufacturing of the electrical steels, which make researchers seek an alternative method to substitute the rotated cube texture for the cube texture. \( (001)[100] \) orientation becomes \( (001)[110] \) if it is rotated by 45° from the rolling direction and is called a rotated cube texture. This texture is obtainable during cold deformation and has a small Taylor factor indicating low strain energy. If the rotated cube texture obtained by cold deformation is controlled by the subsequent annealing, it can be developed largely. Generally annealing of cold worked steels brings about recrystallization texture with a strong \( \{111\}\langleuvw\rangle \) orientation. If both cold deformation is small and annealing temperature is low, only recovery occurs and thus \( (001)[110] \) grains with the small Taylor factor grow at the expense of grains possessing large Taylor factor. Boer and Wieting\(^{11}\) also reported that \( \{001\}||\langle110\rangle \) orientation was obtained by multi-step cold rolling and annealing and grains with low stored energy played a role in the development of the rotated cube texture. Once the rotated cube texture is obtained through cold rolling and annealing processes, it will have the same effect as the cube texture because the core parts for the transformers and motors are punched in the 45° direction from the rolling direction, as shown in Fig. 1. The reason for taking interest in the rotated cube texture is because it is possible to secure more rotated cube texture than the cube texture in cold rolling and to further enlarge it during annealing process.

Grain boundaries of \( \{001\}||\langle110\rangle \) grains are of low angle boundary of which mobility is relatively high. CSL boundaries have generally lower grain boundary energies and higher migration mobility than general grain boundaries.\(^{21}\) Therefore these boundaries are presumably related to the CSL boundaries. \( \Sigma 1 \) boundary exists in low angle boundary and \( \Sigma 3 \) places mainly in twin boundary, which are the typical CSL boundaries. Therefore, the present work focuses on the development of rotated cube texture depending on the repeated cold deformation and annealing and also on the relation of the CSL boundaries with this texture.

2. Experimental Procedure

3% silicon steel was melted in a vacuum furnace and cast into a 30 kg ingot having the chemical composition as shown in Table 1. The ingot was hot rolled to 2.1 mm thickness and the hot rolled samples were performed by multiple processes as illustrated in Fig. 2. Hot rolled bars

Fig. 1. Schematic diagram showing rotated cube orientation on rolled sheet.
were first cold rolled 80% and subsequently first annealed at 700°C for 2 min. The first annealed sheets were secondary cold rolled 10% and were finally secondary annealed at 700°C for 10 min.

The texture development of the specimens obtained from each process was investigated by X-ray diffraction using a texture goniometer. The orientation distribution functions (ODF) were calculated from the pole figure data obtained from measuring {110}, {200} and {211} poles. The analysis of various textures for each process was performed using the calculated ODFs. The intensities of ODF $f(g)$ within 15° of the centerline of each texture in the Euler space were integrated to calculate accurately the volume fraction of the texture components.

### 3. Results

#### 3.1. Change of Textures

##### 3.1.1. Influence of 1st Cold Rolling

Figure 3 reveals the ODF maps which were calculated from the pole figures of each process. In the 1st cold rolled specimens of 80% reduction (Fig. 3(a)), the rolling textures are well developed and $\gamma$ fiber locating at $\Phi_1=0°-90°$, $\Phi_2=55°$, $\Phi_3=45°$ in the Euler space appeared strong, but the subsequent annealing of the cold rolled specimens shows a considerable change in textures in which a reduction of $\gamma$ fiber is noticed (Fig. 3(b)). The second cold rolling of the first annealed specimen (Fig. 3(c)) results in a substantial decrease of $\gamma$ fiber which once appeared strong in the previous process and reveals a random distribution of orientations. The 2nd annealing (Fig. 3(d)) shows little change in the texture development from the previous process. The texture components were more precisely evaluated by calculating volume fractions quantitatively from the ODFs, as illustrated in Table 2.

The rotated cube texture appears predominant compared to the cube and Goss textures which are beneficial for magnetic properties throughout the whole processes from 1st cold rolling to 2nd annealing. In the first process of a large amount of cold reduction, the rotated cube texture reveals 5.3% volume fraction which is more than those of the cube texture and the Goss texture. The Goss texture shows relatively small amount, while the $\gamma$ fiber, one of typical rolling textures, exhibits a large volume fraction of 26.3%.

### Table 1. Chemical composition of the test specimen (wt%).

| Element | C   | Si  | Mn  | Al  | P   | S   |
|---------|-----|-----|-----|-----|-----|-----|
|         | 0.030 | 3.1 | 0.11 | 0.030 | 0.034 | 0.007 |

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3.1.2. Influence of 1st Annealing

Regarding the change of the noticeable textures, the volume fraction of the rotated cube texture was increased by 40% by the 1st annealing but the cube and Goss textures show little change from those in the previous cold rolling, and γ fiber decreased a little. However, as though the stored energy may be accumulated from such a large amount of cold reduction, the rotated cube texture did not develop in a large volume as expected during annealing at such low temperature of 700°C for 2 min. It is obvious that this annealing condition is not sufficient to grow to the recrystallized grains and thus these rotated cube texture and cube texture with a low Taylor factor can not grow properly.

3.1.3. Influence of 2nd Cold Rolling

In the 2nd cold rolled specimens with a reduction of 10%, the rotated cube texture decreased by 49% from the previous annealing but the cube texture changed little and the Goss texture revealed still a small amount while γ fiber decreased by 25%. It is assumed that the decrease in the volume fraction of the rotated cube texture is attributed to the breakdown of rotated cube texture by such a light cold deformation, which means that the rotated cube orientation was changed into other orientations.

3.1.4. Influence of 2nd Annealing

The subsequent annealing of the 2nd cold rolled specimens was performed at 700°C for 10 min and the result showed that all the textures including the rotated cube remained were unchanged from the 2nd cold rolling. This situation implies that such a small cold reduction of 10% is not enough for obtaining sufficient stored energy and thus the textures are not able to develop during annealing at the low temperature for the short time. Actually the reduction of the stored energy in the matrix by lowering the reduction ratio of the 2nd cold rolling was intentional for the present work both to enhance the volume fraction of the rotated cube texture and to avoid the rapid recrystallization causing the development of easy growing textures with high energy. It is assumed that if the stored energy is low, the high energy orientations grow hardly and instead the rotated cube orientation can easily grow. However, the results obtained did not come up to this expectation. That is, the small amount of stored energy evolved from the low cold reduction is not potential to grow the rotated cube orientation too.

3.1.5. Other Noticeable Textures

As seen in Table 2, S component of (123)(634) locating at $\Phi_1=59^\circ$, $\Phi=36.7^\circ$, $\Phi_2=63.4^\circ$ in the Euler space appears fairly strong from the 1st stage cold rolling and increases slightly after the 2nd cold rolling and annealing. Compared to S component, copper (112)<111> and brass (110)<112> components reveal small volume fractions and increase a little after the 2nd cold rolling and annealing processes.

3.2. Change of CSL Boundaries

The frequency of CSL boundaries were analyzed from $\Sigma_1$ to high $\Sigma$ boundaries to find out a relation of the development of the rotated cube texture with $\Sigma$ boundaries. Figure 4 show the frequency of CSL boundaries for the test conditions as well as they show the changes of $\Sigma$ boundaries from the beginning state of the 1st cold rolling to the final annealing process. First of all the dominant $\Sigma$ boundaries are $\Sigma_3$, $\Sigma_7$, $\Sigma_9$, $\Sigma_{11}$, $\Sigma_{15}$, and $\Sigma_{23}$. The $\Sigma_3$ boundary shows the highest frequency and keeps up the similar frequency before the 2nd annealing but decreases during the 2nd annealing. The $\Sigma_3$ boundary is relatively low energy boundary. Therefore, this boundary can grow presumably by consuming the high energy boundaries especially during the 1st annealing. This boundary does not change from the 1st cold rolling to the 2nd cold rolling but decreases negligibly after the subsequent annealing. The $\Sigma_7$ boundary is also one of the dominant CSL boundaries. This CSL boundary reveals a similar frequency from the 1st cold rolling to the 2nd cold rolling but increases during the 2nd annealing process. The $\Sigma_7$ boundary does not grow from the 1st cold rolling to the 1st annealing but grow from the 2nd cold rolling to the 2nd annealing, which implies that, in case of annealing of heavy cold rolling, $\Sigma_7$ boundary with high energy is easily consumed by the low energy boundaries. However, for annealing of the light cold reduction, the $\Sigma_7$ boundary increases because it does not obtain suffi-

| Texture component | Euler angle ($\Phi_1, \Phi_2$) | 1st cold rolling | 1st annealing | 2nd cold rolling | 2nd annealing |
|-------------------|-------------------------------|-----------------|--------------|-----------------|--------------|
| Cube [001]<100>   | (45.0, 45.0)                 | 3.0             | 3.0          | 2.8             | 2.6          |
| Rotated Cube [001]<110> | (0.0, 45.0)                       | 5.3             | 7.4          | 3.8             | 3.6          |
| Goss [110]<001>   | (90.0, 45.0)                  | 1.4             | 1.5          | 2.5             | 2.2          |
| γ fiber [111]<11<0> | (90.0, 55.45)                | 26.3            | 23.4         | 17.6            | 17.5         |
| S [123]<634>     | (59.367, 63.4)               | 5.7             | 5.3          | 6.6             | 6.9          |
| Copper [112]<111> | (90.3526, 45)                | 3.4             | 2.8          | 3.4             | 3.6          |
| Brass [110]<112> | (54.7490, 45)                | 2.3             | 2.5          | 2.9             | 3.1          |

Fig. 4. Frequency of CSL boundaries at each stage of process.
cient energy from the light reduction and thus it is not subject to be consumed by the growth of other orientations. The Σ15 boundary is also a noticeable increase after the 2nd annealing as the Σ7 boundary does.

4. Discussion

The rotated cube texture showed 5.3% in volume fraction during the 1st cold reduction which is relatively higher than the cube and Goss texture and it was increased by 40% by the subsequent annealing at relatively low temperature for short time. That is, the rotated cube texture appeared predominantly at the 1st annealing as seen in Fig. 5 showing the intensity of the (001)[110] orientation along the α fiber. The high reduction by the 2nd cold rolling results in well development of the rolling texture and the subsequent annealing also develops the recrystallization texture fairly well even though both the annealing temperature is low and time is short. The fact which evidences the above results is the appearance of γ fiber which occurs in a large volume before and after the 1st annealing. It is obvious that even at low annealing temperature if the stored energy is largely obtained by such a large cold reduction, recrystallization proceeds very well. The increase in the (001)[110] orientation is apparent at the 1st annealing, which can be explained as the (001)[110] grains with low Taylor factor (low stored energy) can grow by consuming the other grains with high stored energy during annealing process. Thus it is also evident that the texture components of γ, S and copper having a relatively high Taylor factor decrease in volume fraction after annealing. As a matter of fact, from the consumption of these textures, the rotated cube texture develops to some extent during annealing compared to the cube texture, which is similar to Boer and Wierting’s result in which the development of recrystallization texture took place near (001)[110] grains.

In the mean while, the samples which were subjected to the 2nd cold rolling of 10% and the subsequent annealing revealed a decrease in the volume fraction of the rotated cube texture. After 2nd cold rolling of the 1st annealed specimens, the rotated cube texture decreases by 49% and further decreases a little more after the subsequent 2nd annealing. This result indicates that the rotated cube texture under such a light reduction is decreased by transferring to other orientations and also decreases after the subsequent annealing. That is, the small amount of the stored energy obtained from the light reduction lacks of driving force for recrystallization and it therefore is difficult for the rotated cube texture to develop. Especially in the process of the 2nd cold rolling, it is distinctive that the γ fiber decreases remarkably during the 2nd cold rolling which is different from the fact that γ fiber can be developed easily by cold deformation. It means that such a small reduction results in a reduction of γ fiber, but this phenomenon is subject to further study. Even after annealing of the 2nd cold deformation, the γ fiber exhibits little change. On the other hand, the other texture components of S, copper and brass with a large Taylor factor increases a little by each step under these treatments.

In addition, the behavior of CSL boundary according to the each step of processing is also of concern because the Σ boundary is very much related to grain orientations in secondary recrystallization of the electrical steels. First of all, in case of high reduction of the 1st cold rolling, Σ3, Σ5, Σ7, and Σ9 boundaries appear noticeably and Σ3 boundary is most predominant. The Σ3 boundary appears still high even after the subsequent 1st annealing. However, the above CSL boundaries except Σ9 boundary show little change for the 1st cold rolling and annealing.

Again in examining the case of the 2nd cold rolling, it is known that Σ7 and Σ15 boundaries increase predominantly but others show very low frequency. These CSL boundaries are regardless of the rotated cube orientations and thus the increase of these boundaries can hardly be related to the development of rotated cube texture. Consequently, in summary of the relation of the CSL boundary with the development of rotated cube texture, it is obvious that the dominant Σ boundaries of Σ3, Σ5, Σ7, Σ9 and Σ15 are not in relation with the development of the rotated cube orientation.

5. Conclusions

(1) Rotated cube texture was obtained about 5% during the 1st heavy cold rolling 80% and increased by 40% after the subsequent annealing but thereafter both the 2nd light cold rolling 10% and the 2nd low temperature annealing at 700°C were not able to increase the rotated cube orientation. This result assures that a small amount of cold reduction does not activate the growth of the rotated cube orientation and subsequent annealing of such lightly cold deformed materials does not increase it either.

(2) The γ fiber of hard magnetizing orientation revealed a large volume fraction above 20% through the 1st cold rolling and annealing but after 2nd cold rolling and annealing it decreased markedly, which also means that it does not change under low temperature annealing after low cold reduction.

(3) Σ3, Σ7, Σ9 and Σ15 appeared as main Σ boundaries in the present work.

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