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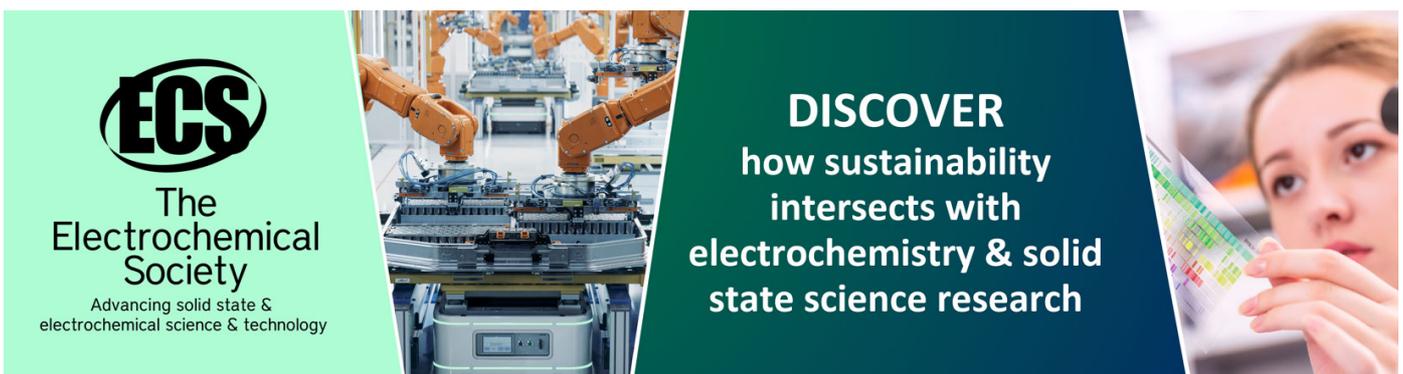
## Improving magnetic properties by optimization of textures in non-oriented electrical steel with initial columnar grains

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# Improving magnetic properties by optimization of textures in non-oriented electrical steel with initial columnar grains

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**Abstract.** This study investigates the processing route to optimize magnetic properties along both rolling and transverse directions, and the evolution of texture during the process is revealed by EBSD technique. The results show that, thinner hot-rolled bands accompanied with coarser structures after normalization are beneficial for promoting the magnetic properties of final sheets. Compared with the 35W300 high-grade NGO steel with a similar composition exhibiting  $B_{50} = 1.71\text{T}$  (along RD)/ $1.67\text{T}$  (along TD), the  $B_{50}$  values of samples obtained by hot rolling to 1.5mm and subsequent processes are equal to or higher than  $1.75\text{T}$  (along RD)/ $1.69\text{T}$  (along TD). Moreover, a greater quantity of  $\{hk0\}\langle 001\rangle$  oriented nuclei result in stronger  $\{hk0\}\langle 001\rangle$  recrystallization texture in recrystallized warm rolled samples heated at  $300^\circ\text{C}$  in advance, and stronger  $\{100\}\langle 0vw\rangle$  texture is achieved in the samples prepared by two-stage annealing method. In addition, the distinct deformation and recrystallization behaviors of  $\{100\}\langle 001\rangle$  and  $\{100\}\langle 110\rangle$  columnar grains are discussed.

## 1. Introduction

Improving magnetic properties of non-oriented electrical steel is a priority for electrical steel manufacturers. The processing technology mainly focuses on the decrease of iron loss in the past years, while higher magnetic induction is essential for improving the product efficiency, and it could be realized by texture control. In general, deleterious  $\gamma$ -fiber texture could be reduced with the increase of hot band grain size, which could conversely promotes  $\{hk0\}\langle 001\rangle$  nucleation inside shear bands and lead to stronger  $\{hk0\}\langle 001\rangle$  texture<sup>[1]</sup>. The texture evolution could also be affected by cold rolling and annealing methods, namely different rolling reduction, rolling and annealing temperatures<sup>[2-3]</sup>.

Our previous study shows that retaining  $\{100\}\langle 0vw\rangle$  texture from initial columnar grains provides a promising way for preparation of non-oriented electrical steel<sup>[4]</sup>. This study further investigates the texture evolution of columnar grains. In addition, the development of  $\gamma$ -fiber and  $\{hk0\}\langle 001\rangle$  texture is investigated as well, thus optimizing the magnetic properties by texture control.

## 2. Experimental

The starting material is a columnar-grained electrical steel cast slab containing 2.5%Si, 0.52%Al and 0.0023%C, with the thickness of 30mm. After heating at  $1200^\circ\text{C}$  for 30min, the slab was hot rolled to 2mm or 1.5mm thick in five rolling passes. For the bands hot rolled to 1.5mm, reheating at  $1200^\circ\text{C}$  for 10min was carried out after three rolling passes. The hot rolled bands were heated up to  $1000^\circ\text{C}$  with a rate of  $5^\circ\text{C}/\text{min}$ , and the annealed samples were named N1 and N2. N2 with the thickness of 1.5mm is thinner than N1, which is 2mm

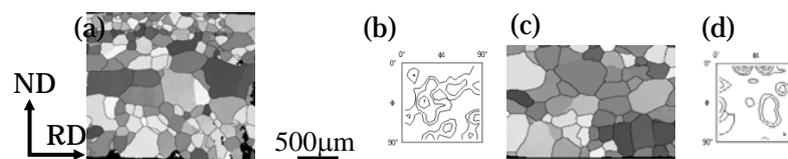
thick, and the thinner hot band leads to lower cold rolling reduction. Then N1 and N2 were further cold rolled and annealed with different methods displayed in table 1, in which quick, slow and two-stage annealing meant annealing at 1000°C for 10min with heating rates of 300°C/min, 5°C/min and firstly annealing at 700°C for 10min, followed by slowly heating up to 1000°C and remained for 10min respectively; and warm rolling meant heating at 300°C for 30min prior to rolling. In addition, the rolled samples from 1.5mm hot band were heated to 700°C to investigate the nucleation behaviors. Textures and microstructures in the cross sections of N1 and N2 as well final sheets were measured by EBSD in Zeiss Ultra 55 FESEM and HKL software. Magnetic inductions at 5000A/m ( $B_{50}$ ) were measured by a single sheet tester in rolling and transverse directions of samples.

**Table 1.** Methods of cold rolling and final annealing

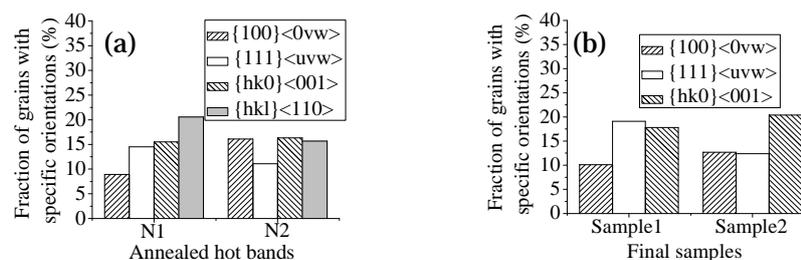
Annealed hot bands	Rolling	Annealing		
		Quick annealing	Slow annealing	Two-stage annealing
N1	Cold rolling	sample 1		
	Cold rolling	sample 2	sample 3	sample 4
N2	Warm rolling	sample 5	sample 6	sample 7

### 3. Results and discussion

As shown in figure 1, both N1 and N2 show recrystallized microstructure, and fewer small grains are observed in N2.  $\{100\}<0vw>$  texture is markedly retained in N2, and  $\{hk0\}<001>$  texture is obtained in both samples. Higher intensity of  $\{100\}<0vw>$  texture in N2 accompanied with weaker  $\alpha$  and  $\gamma$ -fiber is assumed to be related with the recrystallization caused by reheating during hot rolling, showing the similar effect of reducing hot rolling reduction. When N1 and N2 are rolled and annealed, the magnetic inductions  $B_{50}$  values of sample1 are 1.72T(along RD)/1.67T(along TD), reaching the level of 35W300 NGO steel exhibiting  $B_{50} = 1.71T / 1.67 T$ . Moreover, the  $B_{50}$  values of sample2 are higher as 1.75T/1.69T, and stronger beneficial  $\{100\}<0vw>$  and  $\{hk0\}<001>$  textures depicted in figure 2(b) result from their advantage in N2 and stronger heredity after cold rolling to moderate strain and final annealing. Meanwhile, the increasing grain size prior to cold rolling and lower rolling reduction lead to weaker  $\gamma$ -fiber texture in Sample2.

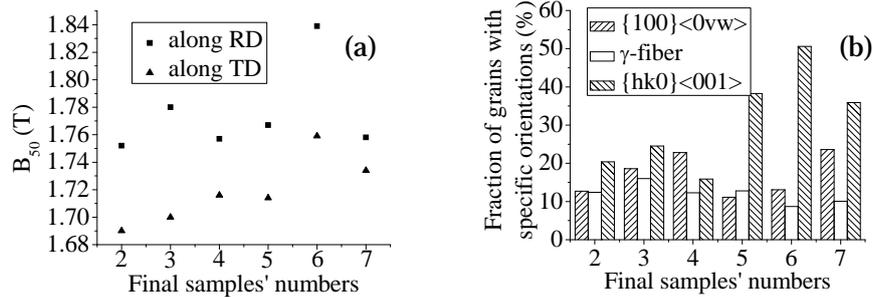


**Figure 1.** Orientation maps and ODFs at  $\phi_2=45^\circ$  section of N1 (a-b) and N2 (c-d).



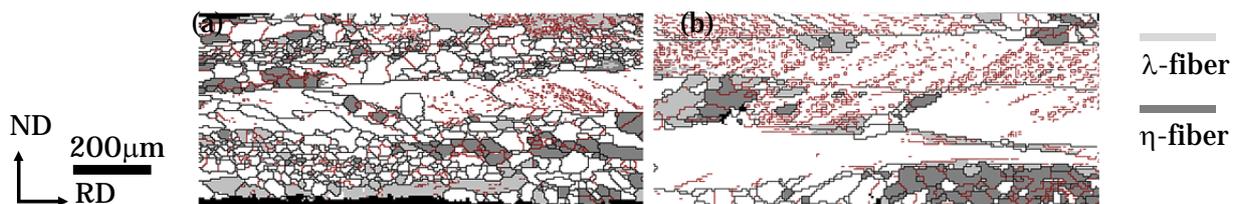
**Figure 2.** Fractions of grains with specific orientations in annealed hot rolled bands (a) and corresponding final samples (b).

As discussed above, thinner hot-rolled bands accompanied with coarser structures after normalization are beneficial for the magnetic inductions of final samples, and the magnetic induction could be further improved with modified rolling and annealing methods. Figure 3(a) illustrates higher  $B_{50}$  in recrystallized warm rolled samples, related with stronger  $\{hk0\}\langle 001 \rangle$  texture in figure 3(b). Better magnetic inductions along TD are shown in the samples by slow annealing and two-stage annealing than quick annealing, and the smallest differences between  $B_{50}$  values along RD and TD are obtained in the samples processed by two-stage annealing, which is in accordance with the highest fraction of  $\{100\}\langle 0vw \rangle$  grains.



**Figure 3.** The Magnetic inductions (a) and fractions of specific oriented grains (b) of final sheets prepared with 1.5mm annealed hot band N2.

To clarify the texture evolution under different processing routes, partially recrystallized samples are measured to investigate nucleation behaviors.  $\{100\}\langle 0vw \rangle$ ,  $\gamma$ -fiber and  $\{hk0\}\langle 001 \rangle$  new grains are all observed in figure 4, while  $\{hk0\}\langle 001 \rangle$  new grains show superiority in numbers than other grains in warm rolled sample, as shown in figure 4(b). The promoted  $\{hk0\}\langle 001 \rangle$  nucleation contributes to stronger  $\{hk0\}\langle 001 \rangle$  texture, and the effect of rolling methods on  $\{hk0\}\langle 001 \rangle$  texture will be discussed in our other paper. The effect of annealing method on  $\{100\}\langle 0vw \rangle$  texture is attributed to varied nucleation behaviors at different temperatures as well as competition between  $\{100\}\langle 0vw \rangle$  and other nucleation.  $\{100\}\langle 0vw \rangle$  nucleation mainly occurs in  $\{100\}\langle uvw \rangle$ - $\{113\}\langle uvw \rangle$  deformed regions, and it is due to stored energy difference. Compared with  $\{113\}\langle uvw \rangle$  new grains, it is suggested that  $\{100\}\langle 0vw \rangle$  new grains show higher nucleation ability at  $700^\circ\text{C}$  [3]. Therefore stronger  $\{100\}\langle 0vw \rangle$  texture is achieved in samples by two-stage annealing, during which nucleation takes place at  $700^\circ\text{C}$ . In contrast, weaker  $\{100\}\langle 0vw \rangle$  textures are displayed in the samples prepared by slow annealing, and  $\{hk0\}\langle 001 \rangle$  texture is even stronger, especially in warm rolled samples, which is in correspondence with the quantity difference between  $\{100\}\langle 0vw \rangle$  and  $\{hk0\}\langle 001 \rangle$  new grains in figure 4(b).  $\{hk0\}\langle 001 \rangle$  nucleation occurring at shear bands takes place at the earliest stage of recrystallization [5], and slow annealing could provide longer period for its nucleation and growth, reducing other texture consequently. In addition, there may exists effect of recovery on the stored energy and nucleation ability of  $\{100\}\langle 0vw \rangle$  and other grains, while more deep research is necessary to verify the effect and explain it.



**Figure 4.** Orientation maps of partially recrystallized cold rolled (a) and warm rolled (b) samples.

It is worth to note that specific deformation and recrystallization behaviors of  $\{100\}<0vw>$  columnar grains, especially Cube $\{100\}<001>$  and Rotate-Cube $\{100\}<011>$  grains, exert extreme influence on the texture evolution along the processing routes<sup>[4]</sup>. Shear regions are obtained near the surface, and the effect of columnar grains mainly exists in the center layer of hot rolled bands. Initial  $\{100\}<011>$  grains transform to  $\alpha$ -fiber deformed areas after hot rolling. These  $\alpha$ -fiber areas would show strong heredity during following processes, and no nucleation sites for beneficial  $\lambda$ -fiber or  $\eta$ -fiber grains could be provided by them. However, fully recrystallization microstructure is obtained after long period normalization annealing in this study, which means that large  $\alpha$ -fiber deformed grains after hot rolling are consumed, implying that the unbeneficial effect of initial  $\{100\}<011>$  grains is largely restrained. In contrast, initial Cube grains contribute to  $\{100\}<001>$ - $<012>$  texture in annealed hot bands, and then Cube or  $\{100\}<012>$  texture can be achieved by the retaining after deformation at medium strain and subsequent recrystallization<sup>[3]</sup>. In particular, the intensity of  $\{100\}<001>$ - $<012>$  texture is higher in annealed hot band N2 prepared with hot rolling and additional reheating processes, and  $\alpha$ -fiber texture is weaker in the same sample, both leading to optimized texture in final samples

#### 4. Conclusion

- 1) The magnetic properties are optimized by improving  $\{100\}<0vw>$  and  $\{hk0\}<001>$  textures in 2.5wt.%Si-0.52wt.%Al columnar-grained electrical steel. Thinner hot-rolled bands accompanied with coarser structures after normalization are beneficial for the magnetic inductions), the  $B_{50}$  values of samples obtained by hot rolling to 1.5mm and subsequent processes are equal to or higher than 1.75T (along RD)/1.69T (along TD).
- 2) A greater quantity of  $\{hk0\}<001>$  oriented nuclei result in stronger  $\{hk0\}<001>$  recrystallization texture in recrystallized warm rolled samples, and stronger  $\{100\}<0vw>$  texture is achieved in the samples prepared by two-stage annealing methods.
- 3) The unbeneficial effect of initial  $\{100\}<011>$  grains is restrained by long period normalization annealing, and the beneficial  $\{100\}<001>$ - $<012>$  texture related with initial Cube grains is stronger in annealed hot band prepared with hot rolling and additional reheating.

#### Acknowledgments

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