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Analyses of texture memory, surface-effect-induced transformation texture and variant selection in low graded electrical steels

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Abstract. This study investigates the retaining of both {100} texture and topographic structure of columnar grains in cast slabs of industrial low graded electrical steels in terms of texture memory and variant selection. In addition, phase transformation treatment is conducted on industrial low graded electrical steels to explore the possibility of producing {100} texture by surface effect. The results show that the texture memory in columnar grains of cast slab can be explained by the directional cooling and internal thermal stress. The abundant Σ3 grain boundaries of small equiaxed grains within coarse columnar grains are detected, which can reduce transformation strain effectively. After phase transformation annealing, {111} and {100} texture memories with equiaxed grains in recrystallization type are resulted in commercial sheets due to the presence of P and Al elements which restrict surface-effect induced transformation texture. In comparison, strong {100} texture and columnar grains are formed in a laboratory-melt sheet as surface effect induced transformation texture by preferred nucleation at surface and preferred growth into sheet centre layer.

1. Introduction

The textures in commercial non-oriented electrical steels are generally optimized by the control of deformation and recrystallization parameters irrespective of their grades or silicon contents. The favorite {100} texture in such condition takes at maximum only about 20% in volume fraction. In contrast nearly 80% volume fraction of beneficial {100} texture can be obtained by phase transformation in pure Fe or slightly alloyed Fe with columnar-grained structure in final sheets, which is confirmed by many researchers[1-4]. The texture memory effect is often detected in steels during recrystallization and α→γ→α transformation, and the crystallographic orientation relationships are usually maintained between the parent and new phase which is often subjected to variant selection. Without such variant selection, texture will be normally weak during transformation. Yet texture memory or variant selection is not equal to the presence of strong phase transformation texture, it is often seen that phase transformation texture is quite different to the rolling texture of ferrite before transformation. If phase transformation proceeds uniformly in steel sheets, {111} texture or nearly random orientations can also be resulted. If nucleation preferentially appears at sheet surface in pure hydrogen after rolling and successive growth into sheet center takes place, columnar structure with strong {100} new texture can be obtained (the so-called surface effect induced transformation texture), so that magnetic properties can be improved.

Based on the fact that strong {100} texture can be produced by rolling and subsequent phase transformation annealing in low graded electrical steels, this work aims to investigate the role of texture memory and variant selection during δ→γ→α transformation in cast slabs of low graded electrical steels containing dominant columnar grains. The phase transformation treatment is performed on the industrially low graded electrical steels to explore the possibility of producing {100} texture by surface effect. The purpose of this study is to provide fundamental principles for the potential industrial application of low graded non-oriented steels by special transformation treatment.

2. Experimental

The starting material is a columnar-grained industrial low graded electrical steel cast slab containing 0.35%Si, 0.002%C, 0.13%Mn and 0.14%P. A dilatometer was used to measure the critical phase transformation temperature: A_{c1}=980°C, A_{c3}=1090°C; A_{r1}=938°C, A_{r3}=973°C. The deformation process for four samples is listed in table 1. The cast slab was heated at 1100°C for 30min and hot rolled from 10mm to 2mm thick in three rolling passes. The finish rolling temperature is about 800°C (finish hot rolling in ferrite area). After different deformation processes, the phase transformation annealing of samples is conducted in a tube furnace under H_2 atmosphere with a flow rate of 8L/min. Samples were pushed into the furnace at 1100°C and held for 5min, subsequently the samples were cooled to 900°C at a cooling rate of 300°C/h. After cooled to 900°C, the samples were pulled out from the furnace and cooled in a chamber at room temperature. Textures and microstructures in the cross sections of different samples were measured by the electron back-scatter diffraction (EBSD) system of HKL Oxford-Instruments, mounted on a ZEISS ULTRA55 field-emission SEM. The orientation of maximum deviation angle is set to 15° in this experiment.

Table 1. Deformation process before phase transformation annealing.

Samples	deformation process
Sample 1	No deformation(original cast slab)
Sample 2	Hot rolling(2.0mm)
Sample 3	Hot rolling(2.0mm)-cold rolling(0.2mm)
Sample 4	Hot rolling(2.0mm)-cold rolling(0.6mm)

3. Result and discussion

Two types of texture memories are observed in this steel. The first type occurs in cast slab containing coarse columnar grains and is free from external strain, whereas the second one appears in the strongly rolled and recrystallized sheet subjected to a final special phase transformation. Figure 1 shows the grain orientations and microstructure of cast slab which was subjected to twice transformation of δ→γ→α during cooling. The EBSD data reveal that the area fraction of columnar grains with nearly {100} orientation (the maximum deviation is 15°) is about 70%. As the twice transformations are free from external strain, the reason for such texture memory is attributed to the directional cooling from slab plate surface to plate centre and the internal strain due to cooling. It is well known that there are 24 variants in the case of a K-S orientation relationship ($\{111\}_{fcc}//\{110\}_{bcc}$ and $<110>_{fcc}//<111>_{bcc}$). In order to reduce the transformation strain as much as possible, plenty of Σ3 variants (red lines in Figure.2b) which generate lower strain are detected between coarse columnar grains and small equiaxed grains. It indicates that variant selection is strong when columnar {100} δ-grains transform into columnar {100} α-grains.

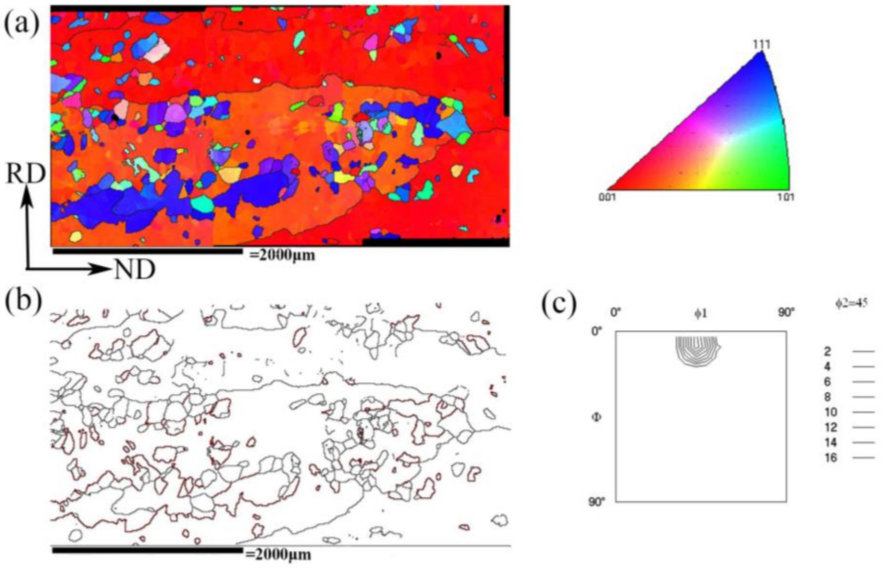

Figure 1.EBSD data for the cast slab: (a)IPF-Z map; (b) GB distribution map (red lines represent Σ3GB); (c) ODF at φ_2 = 45° section.

Figure 2 presents the EBSD data for the further treated cast slab. A further circle of phase transformation annealing ($\alpha_1 \rightarrow \gamma \rightarrow \alpha_2$) at 1100°C is performed without external straining on the cast slab, thus four times of transformation occur in the steel. It is seen that after this treatment, still 65% near {100} (the maximum deviation is 15°) columnar grains together with plenty of Σ3 variants are resulted. Thus the texture memory and variant selection in coarse columnar grains are strong.

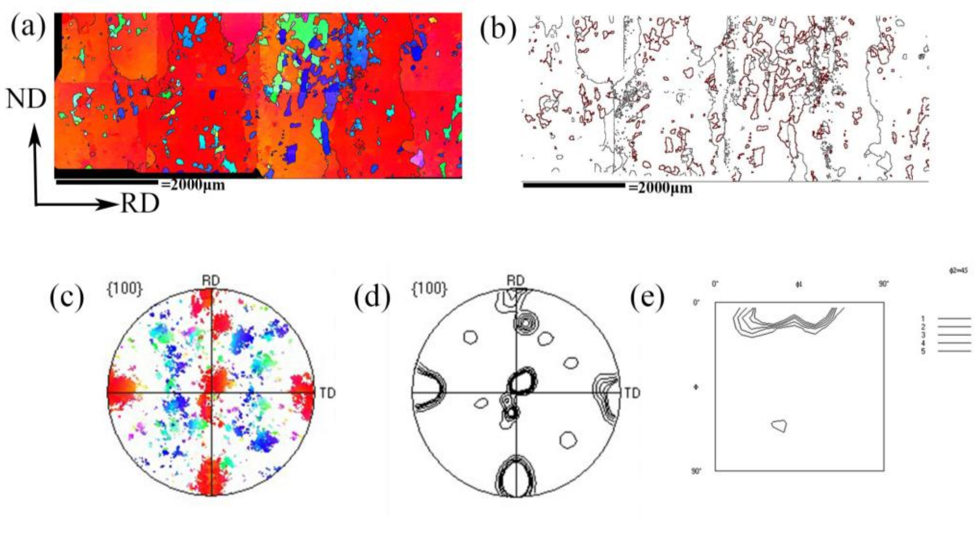

Figure 2. EBSD data for sample1 after phase transformation annealing: (a)IPF-Z map; (b) GB distribution map (red lines represent Σ3GB); (c, d){100} pole figures; (e)ODF at φ_2 = 45° section.

Figure 3 displays the EBSD data for the cross sections of hot rolled sheet (sample2), cold rolled sheets (sample3 and sample4), respectively. It shows that {110}<001>/<112> and {111}<112>/<110> orientations are resulted at surface region and centre layer in the hot rolling sheet respectively (Figure 3a,b). The cold rolled sheets with different thicknesses (0.6mm for sample3 and 0.2mm for sample4) present similar rolling textures comprising the α-fibre and the {111}<110> textures.

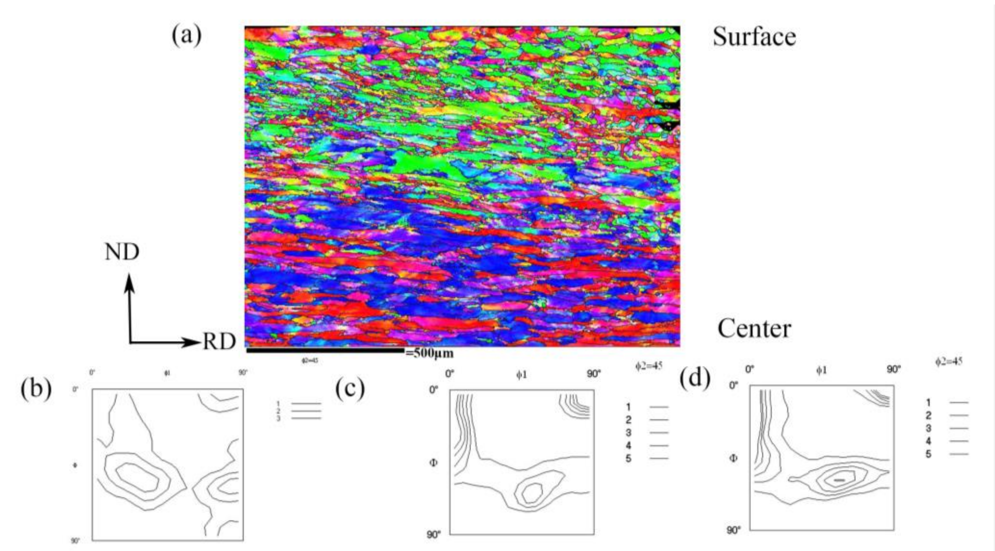

Figure 3. EBSD data for the cross sections through thickness of the deformed sheets: (a) IPF-Z map for Sample2 (half of the thickness); (b) ODF at φ_2 = 45° section for Sample2; (c) ODF at φ_2 = 45° section for sample3; (b)ODF at φ_2 = 45° section for Sample4.

Figure 4 and Figure 5 display the EBSD data for sample3 and sample4 after transformation annealing ($\alpha_1 \rightarrow \gamma \rightarrow \alpha_2$) at 1000°C in pure H_2, respectively. Instead of columnar grains with near {100} texture as reported in the study of Zhang[4], only equiaxed grains with mainly {111}<112> and {100}<021> orientations are obtained in the sheets after phase transformation annealing, as seen in Figure 4(e) and Figure 5(e), namely the transformation texture here belongs to the recrystallization type, which is also a kind of texture memory effect. The reason for this kind of texture memory lies in the uniform transformation throughout the sheet thickness, rather than only in the surface for the columnar grain structure. In addition, less Σ3 variants are produced, see Figure 4(b) and Figure 5(b).

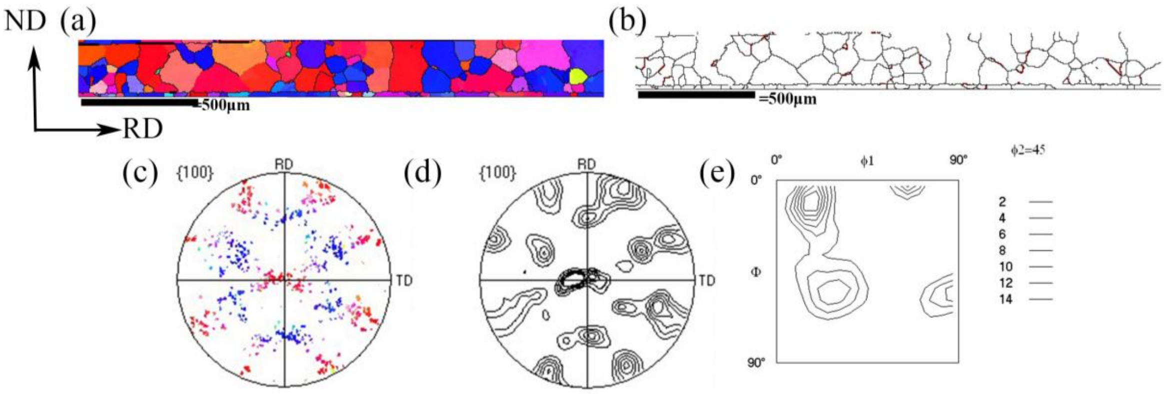

Figure 4. EBSD data for sample3 after phase transformation annealing: (a)IPF-Z map; (b) GB distribution map (red lines represent Σ3GB); (c, d){100} pole figures; (e)ODF at φ_2 = 45° section.

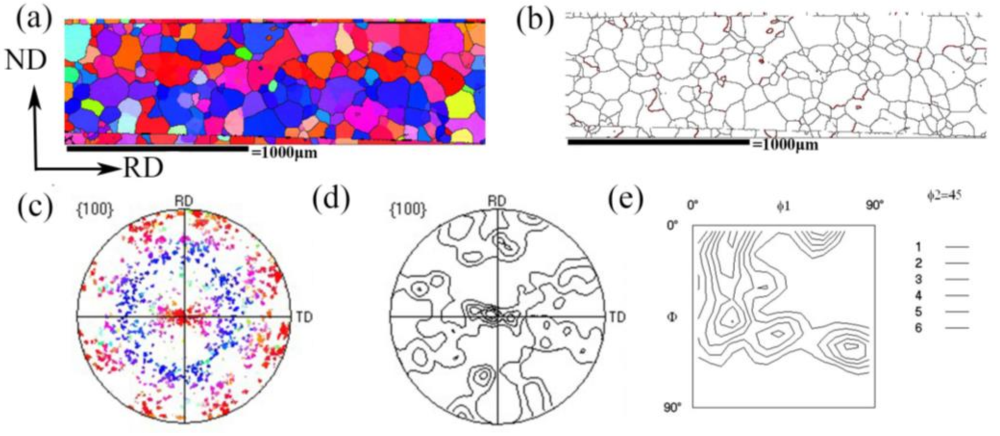

Figure 5. EBSD data for sample4 after phase transformation annealing: (a)IPF-Z map; (b) GB distribution map (red lines represent Σ3GB); (c, d){100} pole figures; (e)ODF at $\varphi_2 = 45°$ section.

For comparison, Figure 6 shows the EBSD data for Fe-0.5Si-0.5Mn steel sheet (a laboratory-melt steel, 0.5mm in thickness) after phase transformation annealing. The near {100} texture and columnar grains were formed in this laboratory-melt steel during phase transformation annealing in H_2 atmosphere, where surface effect induced transformation texture is prevailing and the near {100} texture is a new texture component formed by preferred nucleation at surface and preferred growth into sheet centre layer. The variant selection is also strong because only one new variant is formed during the growth of {100} columnar grain.

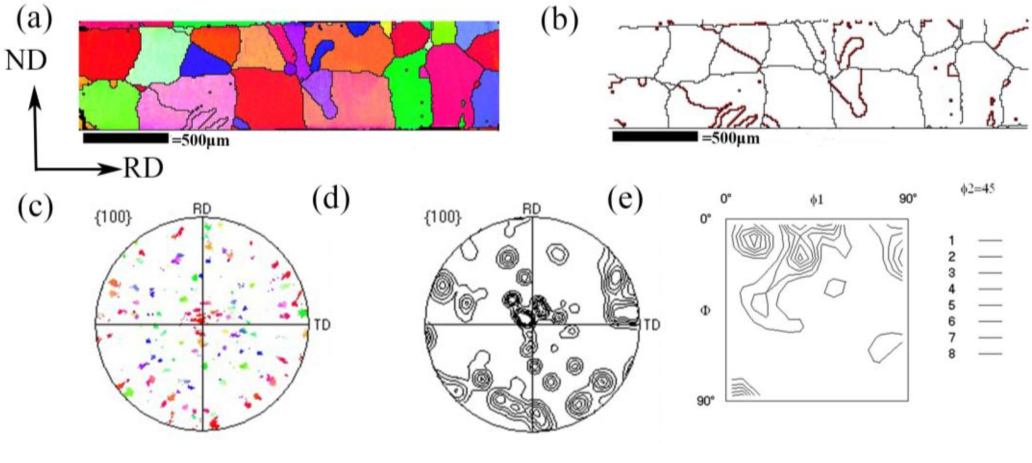

Figure 6. EBSD data for Fe-0.5Si-0.5Mn steel sheet (laboratory-melt steel, 0.5mm in thickness) after phase transformation annealing: (a)IPF-Z map; (b) GB distribution map (red lines represent Σ3GB); (c, d){100} pole figures; (e)ODF at $\varphi_2 = 45°$ section.

By comparing the textures and microstructures of commercial steels with the laboratory-melt steels after phase transformation annealing in pure H_2, it is seen that surface-effect induced phase transformation and columnar grain microstructure are less significant in the commercial steel sheet containing 0.12%Al and 0.14%P, which may influence the surface effect during phase transformation annealing. In order to analyze the effect of element distribution on microstructure development, a glow discharge spectrometer (GDS) is used to determine the depth profiles of different elements from surface to inside, as shown in Figure 7. The results indicate that SiO_2 film forms in the surface and Al and P are segregated in the surface. The surface effect may weaken due to the SiO_2 film and the segregation of Al and P in the surface. The presence of P and Al element segregation at surface leads to the uniform nucleation in whole sheets, thus the columnar grains are hard to nucleate preferentially at sheet surface during α→γ→α transformation.

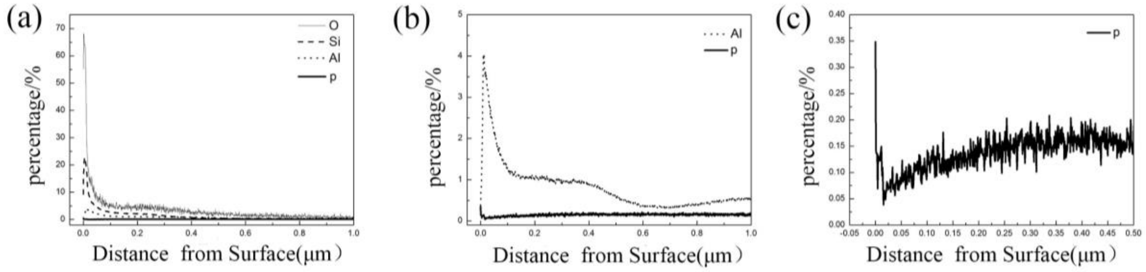

Figure 7. Glow discharge date profiles for the sample3 after phase transformation annealing.

4. Conclusion

1) {100} texture memory in coarse columnar grains during δ→γ→α and α_1→γ→α_2 transformation in the cast slab is observed. The texture memory of strong {111} and weak {100} in recrystallization type is also detected after phase transformation treatment of rolled sheets in pure H_2. The difference between them is attributed to the fact that the directional transformation occurred in the first case and throughout in whole sheet at same time in the latter case. The variant selection is strong in both cases.
2) Surface effect induced transformation texture of mainly {100} and columnar-grained structure are formed by preferred nucleation at surface and preferred growth into sheet center layer. Variant selection is also strong in this case.
3) The presence of P and Al elements in commercial electrical steels restricts surface-effect induced transformation texture by probably segregation at sheet surface， which leads to the uniform nucleation in whole sheets.

Acknowledgements
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