Texture and Deformation Behavior through Thickness Direction in Strip-cast 4.5wt% Si Steel Sheet

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Fe–4.5wt%Si strips were made using vertical type twin-roll strip casting process, and the microstructure and texture of as-cast strips were studied through thickness direction. The heterogeneity of the texture and microstructure through thickness direction was observed. Between the subsurface layer and the middle layer, Goss texture, with the subgrains of low angle grain boundary was evolved by the shear deformation. In the center layer, major rolling and recrystallization textures with minor solidification texture were evolved.

The deformation behavior during strip casting process was simulated by hot rolling of Al alloy with temperature gradient through thickness direction. And the shear and normal strains distribution through thickness direction were measured. The heterogeneity of the texture and the microstructure through thickness direction resulted from the strength gradient, which originated from the temperature gradient through thickness direction.

KEY WORDS: Fe–4.5wt%Si; Twin Roll Strip Casting; deformation behavior; texture; hot rolling strength gradient; temperature gradient.

1. Introduction

The sheets or laminations used as transformer cores are usually made from Si steel sheet. It would be advantageous to use high silicon content of above 4wt% but such alloys are brittle and hard to be cold rolled. The grain oriented silicon steel has been of considerable fundamental and technological interest to increase the sharpness of Goss orientation {110}\langle100\rangle for the improvement of the magnetic properties of the alloys. Although the manufacturing process has been well established, the process is still complicated. Recently, to reduce the processing steps, strip casting and melt spinning have been proposed. The progress in strip-casting technology provides a possibility to manufacture silicon steel sheet by a simpler processing than the conventional process, because the strip casting process can supply a silicon steel strip with the same thickness and width as those of hot rolled strip. This offers a possibility to eliminate the continuous casting and hot rolling processes in the conventional manufacturing process of the grain oriented silicon steel.

In these days, while the technological issues associated with strip casting are currently being addressed worldwide by the steel industry, a fundamental issue to be overcome is the control of the microstructure and texture in the strip cast products. The solidification and deformation conditions during strip casting are significantly different from those in conventional processing. The texture and the deformation behavior of strip-cast Si steel strips according to the casting condition or process parameter have not yet been fully understood. Raabe examined the texture of strip cast austenitic stainless steel and ferritic low carbon steel strip. Choi reported the variation of texture both in roll-width and through thickness direction of AISI430 stainless steel produced from a vertical type twin roll strip cast. Takatani characterized twin roll strip cast steels by Electron Backscattered Diffraction (EBSD) technique and numerically simulated the formation of grain structure by three-dimensional Cellular Automation-Finite Element model.

In the present study, Fe–4.5wt%Si strips were produced using the vertical type twin roll strip caster and the microstructure and texture through thickness direction were studied by the optical metallography and the quantitative X-ray texture analysis. The deformation behavior of a strip during strip casting was experimentally simulated by hot rolling of Al alloy with temperature gradient through thickness direction. The object of this simulation was to observe the effect of temperature gradient through thickness direction when a strip was hot rolled. Moreover, in Al alloys, because oxide scale was not formed at the high temperature, the grid could be observed easily after hot deformation.

2. Experimental Procedure

2.1. Strip Casting

Fe–4.5wt%Si steel strips with 100 mm width and 1.5 mm thickness were produced from the vertical type twin roll strip caster. The superheat of liquid steel was controlled to be 20°C. The chemical composition of the as-cast strip is
given in Table 1. The schematic diagram of the twin-roll strip caster is shown in Fig. 1. Hole-type nozzle was positioned at the center of the tundish. Molten metal was supplied from an induction furnace to the tundish by using a temperature-controlled ladle. Specimens for metallographic examination were etched with Nital (2 vol% Nitric acid + 98 vol% ethanol) reagent. The microstructure of the specimens was observed at the transverse direction by using optical microscope and EPMA. At the normal direction, subgrain boundaries in the subsurface layer were investigated by using transmission electron microscope.

2.2. Texture Measurement

The texture variation of the as-cast strip was investigated through thickness direction. The position through thickness direction can be used by a parameter $s$, defined as $s=2a/d$, where $a$ and $d$ are the distance from the center layer of strip and the thickness of the strip, respectively. The parameter $s$ is called the normalized thickness. To analyze quantitatively the texture of the strip, three incomplete pole figures, \{110\}, \{200\}, \{211\}, were measured in the range of the polar angle $\alpha$ from 0° to 70° with Co K$_\alpha$ radiation in the Seifert D3000 with PTS goniometer. Samples for pole figures measurement were etched at room temperature in a solution of 90 ml H$_2$O$_2$ and 10 ml HF for the stress relieving from the mechanical polishing. ODF was calculated from the measured pole figures by WIMV method. The orientation of the subgrain in subsurface layer was investigated by the EBSD, which was operated by Link Opal system at JEOL 6300 SEM.

2.3. Temperature Gradient Hot Rolling Simulation during Strip Casting Process

The deformation behavior during strip casting was simulated by hot rolling of Al alloy with temperature gradient through thickness direction, called the temperature gradient hot rolling simulation. Figure 2 shows a schematic diagram of the temperature gradient hot rolling simulation. The curved plate of Al-0.1wt%Cu alloy was tightly placed on water-cooled roll surface. The plates had the same radius of curvature with that of strip caster roll and 1 mm × 1 mm grids were marked on the transverse side of the plates. To measure the temperature along the thickness direction, five thermocouples were fixed through the thickness direction in one side of the plate. When the surfaces of the plates were heated to 600°C, roll contact temperature was measured as 530°C. The heated plates were rolled with 20% area reduction. After cooling the plates, shear and normal strains were measured from the deformed grids along the thickness direction.

3. Results

3.1. Microstructure

Figure 3 shows the optical micrograph of the strip-cast 4.5wt% Si steel at longitudinal section. The strip-cast silicon steel shows a heterogeneous microstructure through thickness direction and equiaxed grains of about 200 μm were observed near the surface region ($s=1.0–0.6$). In the middle layer ($s=0.6–0.1$), the columnar dendrites were observed from the surface layer to the center layer. Equiaxed grains of about 10 μm were observed in the center layer ($s=0.1–0.0$). Figure 4 shows optical micrograph of the sheet-deformed subgrains in the subsurface layer ($s=0.8–0.6$). Figure 5 shows transmission electron micrograph of
the subgrain boundary inside the shear deformed grains in the subsurface layer. The subgrain boundaries were consisting of regular dislocation network. **Figure 6** shows EPMA analysis map and line profile along the thickness direction, which shows a negative segregation of Si in the center region of the as-cast strip.

### 3.2. Texture

**Figure 7** shows measured ODFs at various thickness of the strip cast 4.5wt% Si steel. Fig. 7(a) shows that \{100\}-(uvw) fiber evolves in the surface layer of the strip. It is well known that \{100\}-(uvw) fiber typically appears during solidification. In the middle layer of \(s=0.8, 0.6, 0.4\), the Goss \{110\}(001) components have the maximum ODF value as shown in Figs. 7(b), 7(c) and 7(d), respectively. Goss component is the typical shear deformation texture of BCC metals. In the center layer of \(s=0.2\) and 0.0, the \{100\}-(uvw) components and \(\alpha\) and \(\gamma\)-fibers are evolved as shown in Figs. 7(e) and 7(f). \(\alpha\) and \(\gamma\)-fiber are the typical rolling texture according to the plane strain compression, and \(\gamma\)-fiber is also appeared in the recrystallized structure. **Figure 8** shows the orientations of the subgrains in the subsurface layer from the EBSD measurement. Normal direction of the grain is parallel to (110) and rolling direction is parallel to (001). As shown in the Fig. 8(b) and 8(c), these subgrains have the misorientation angle of about 3 degree.

### 3.3. Temperature Gradient Hot Rolling Simulation

**Figure 9** shows the optical micrographs of marked grid before and after temperature gradient hot rolling experiment of strip casting process. **Figure 10** shows the measured shear strain and normal strain and effective strain.
from the deformed grid. The amount of the shear strain decreased from the surface to the middle layer, but the normal strain and effective strain through thickness direction increased from the surface to center layer. The effective strain can represent the total deformation during experiment. The measured shear strain shows that the normal deformation is dominant in the center layer and the shear deformation is dominant in the surface layer.

4. Discussion

In Fig. 3, the equiaxed grains were observed from the surface to the middle layer ($s=1.0–0.6$) and the columnar dendrites were observed from the middle to the center layer ($s=0.6–0.1$). The various parameters, which determine the microstructure and texture in the cast strip, include the superheat, the casting speed, the heat transfer characteristics between the solidifying strip and the rolls, and the flow characteristics of the incoming liquid metal. Figure 11 shows the schematic diagram of melt pool in twin-roll strip casting process. Melt pool can be divided into three parts such as solid layer, mushy zone and liquid pool. The solidified layers from rolls meet at the solidification end point. When the solidification end point was positioned above the roll nip point, roll separating force was excessive and the strip was hot rolled.\(^{12}\) The distance from the nip point of rolls to the solidification end point, $h$ value, is geometrically related with the reduction ratio, $R$, of the strip as follows.

$$R = 1 - \frac{t_0}{(t_0 + 2r) - \sqrt{r^2 - h^2}}$$

where $t_0$ and $r$ are strip thickness at nip point and roll radius, respectively.

Figures 7(e) and 7(f) show that the typical rolling textures consisting of $\alpha$ and $\gamma$ fiber are evolved in the center layer of as-cast strip. Because the temperature of the center layer is the highest,\(^{13,14}\) the center layer of the strip is highly deformed by the plane strain compression during strip casting. $\alpha$ and $\gamma$ fiber were evolved in the center layer of hot rolled ferritic steel sheets.\(^{15–17}\)

In strip casting process, roll separating force can be related with the centerline segregation of the strip. Yamauchi et al. investigated the negative segregation in the center region of a strip-cast strip.\(^{19}\) Fujita et al. reported that the negative segregation in the center region of the strip could happen at high roll separating force. The negative segregation could be caused by the phenomenon that the mushy state steel with concentrated solutes was squeezed out, when two shells encountered and began to be reduced by two rolls.\(^{20}\)

When C content is less than 0.01wt%, Fe–4.5wt%Si steel
has no $\alpha-\gamma$ transformation.\textsuperscript{21) Because $\alpha$-iron and ferritic steels are the materials of high stacking fault energy, dislocation climb and cross-slip occur readily, and therefore dynamic recovery can easily take place in the $\alpha$ phase during hot deformation.\textsuperscript{22)} In this study, the tangled cell walls, which had been formed by hot deformation during the strip casting, became regular dislocation networks as shown in Fig. 5 and low angle grain boundaries as shown in Fig. 4 and Fig. 8 and the number of dislocations in the cell interiors had diminished by dynamic recovery.

The observed rolling texture of $\alpha$ and $\gamma$ fiber as shown in Fig. 7 and the negative segregation in the center layer and the subgrains in the subsurface layer showed that the strip was cast at the condition that the solidification endpoint was located above the roll nip point and the solidified strip was hot rolled.

The reason of the heterogeneous deformation was the strength gradient through thickness direction, and the strength gradient was originated from the temperature gradient through thickness direction.\textsuperscript{10) The solidified surface of the strip near roll was harder and stronger than the inner layer, and the center layer of high temperature was the softest. As shown in Fig. 7, plane strain compression texture of $\alpha$ and $\gamma$-fiber was evolved in the center layer ($s=0.0$, $s=0.2$), but solidification texture of $\{100\}uvw$ components was observed in the surface layer ($s=1.0$) and shear texture with a maximum at the Goss component, $\{011\} \{100\}$ was observed in the subsurface layer ($s=0.8–0.4$). These texture distribution in the surface and subsurface layer showed that the initially solidified surface layer remained in undeformed state due to their high strength, but the subsurface layer, which was relatively softer than the surface layer, was shear deformed during strip casting.

In hot rolled ferritic steels, Goss orientation remained at the surface layer and subsurface layer under high frictional force between roll and specimen and a strong rolling texture consisting of sharp $\alpha$ fiber and weaker $\gamma$ fiber evolved in the center layer.\textsuperscript{15–17)} At the casting condition that solidification end point was located above the roll nip point, the texture distribution through thickness direction of as-strip cast strip was almost similar to that of hot rolled sheet. Raabe reported that the nearly random orientation distribution evolved during strip casting and inhomogeneous texture developed during hot rolling.\textsuperscript{16) The austenitic steels revealed weak textures close to $\{001\}uvw$ fiber and low carbon strips showed textures close to the $\{111\}uvw$ fiber, or revealed a weak texture with minor components close to $\{001\}uvw$ fiber.\textsuperscript{6,7)} Takatani et al. showed that grains had a random crystallographic orientation at the surface of the sheet in contact with the turning rolls, but in the middle ($s=0.8–0.0$) of the sheet, the grains exhibited the slightly inclined (100) texture in which the average dendrite trunk direction is not exactly aligned with the thermal gradient.\textsuperscript{9) The strip casting condition by Takatani et al. was that solid shells formed on the surface of the rolls met at the minimum gap point (roll nip point), that was, solidification end point was located at the roll nip point, and hot deformation was not taken into account in the simulation of grain structure formation.\textsuperscript{9)}

As shown in Fig. 10, normal strain had the maximum value of 3% at the center layer and decreased along thickness direction and the shear strain showed vice versa. The temperature along thickness direction during strip casting was the highest at the center layer and decreased to the surface layer.\textsuperscript{20) Thus the mechanical strength at the surface is higher than that of center layer, leading to smaller the effective strain at the surface layer. Figure 12 shows that the schematic diagram of the deformation behavior of a strip during a strip casting process at the condition that the solidification endpoint was located above the roll nip point. The center layer was deformed under the plane strain compression and the subsurface layer was shear deformed.

5. Conclusion

Using the twin roll strip caster, Fe–4.5wt%Si steel strip was cast on the condition that the solidification endpoint held above the roll nip point. Goss texture was evolved between the subsurface and the middle layer of as-cast strip. In the center layer, $\alpha$ and $\gamma$-fiber was evolved. In the surface layer, $\{100\}uvw$ solidification texture was observed.

Hot rolling deformation during casting and the strength gradient by the temperature gradient through thickness direction during strip casting cause this texture distribution. The subsurface and middle layer were shear deformed and the center layer was deformed under the plane strain compression. In the surface layer, the initially solidified hard layer remained in undeformed state.

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References