The Effect of Annealing Temperature on Recrystallization Texture and Magnetism Property of Non-oriented Silicon Steel under Asymmetrical Rolling Process

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Abstract. The effect of temperature on the recrystallization texture and microstructure of non-oriented silicon steel under asymmetrical rolling condition was studied and the relationship between the magnetism property and recrystallization texture was discussed. The results show that the texture intensity is higher at the fast roller side than that at the slow roller side, but the texture component of recrystallization texture is almost the same under different annealing temperature. At 750 ℃, the main texture component is γ texture (<111>∥normal direction), and the texture (<110>∥rolling direction) components become weak. At 850 ℃, the main texture components are {111}<110> and {111}<112> texture components. With further increasing of the temperature, the strength of {111}<110> and {111}<112> texture does not change, but they tend to disperse and change to {118} and {1115}, and {001} plane texture. The results also indicate that the annealing temperature has significant influence on the iron-loss, but has no obvious influence on the magnetic induction.

1. Introduction
Non-oriented silicon steel is widely used for various motors, because it has the same magnetism in all respective directions. Due to the need for energy saving, reduced iron loss became an important subject[1]. There are many factors affecting iron loss, such as chemical composition, inclusions, processing and heat treatment system. The factors which affect the hysteresis loss, eddy current loss and anomalous eddy current loss are different, and some factors have the opposite effect, and the ultimate performance of these components in the iron loss is the combined result. Hysteresis loss is dominant in the non-oriented silicon steel; therefore, to reduce the thickness and improve the texture is an effective way of reducing the iron loss[2]. Silicon steel [001] direction is the easy magnetization direction. By optimizing the process to obtain [001] direction of the preferred orientation is an effective way to obtain high-quality silicon steel sheet. Recrystallization annealing is an important method to control and change the composition, structure and performance of metals and alloys in industrial production. The recrystallization texture of the annealing system, sometimes is the same with the deformation texture, sometimes is different from the deformation texture. The textures have very important influence on the technological properties and usage performance, and thus it is crucial to control the texture of the material. The non-oriented silicon steel used in the rotating magnetic field requires magnetically isotropic. The easy magnetization direction can be achieved in all directions on its rolling surface and the (100) surface can be arranged without changing the magnetic induction, and thus reduce the iron loss[3]. There is not much research on high-grade non-oriented silicon
steel[4,5,6,7,8,9]. High-grade non-oriented silicon steel was selected in this study. After asynchronous rolling and recrystallization annealing, with the help of the three-dimensional orientation distribution function, the effect of annealing temperature on recrystallization texture and magnetism was investigated.

2. Experimental Methods
Normal treated non-oriented silicon steel with thickness of 2.2 mm was used. The chemical compositions are listed in Table 1. The surface rust of the raw materials was removed with acid wash and then cold-rolled to the thickness of 0.5 mm with the speed ratio of 1.19 (the ratio between lower roller and upper roller phase speed) and the percentage of compression of 77.3%. Size of rectangular sample is 20×18 mm and 100×30 mm. The recrystallization annealing tests were conducted under 750 °C, 800 °C, 850 °C and 900 °C, respectively. Texture measurements were conducted on the PHILIPS X’Pert X-ray diffractometer. Three incomplete polaro graphs of \{110\}, \{200\}, and \{112\} on the fast and slow side of the roller surface were obtained with Schulz back-reflected method. The fast roller side is marked as “R”, and the slow roller side is marked as “S”. The ODF of $l_{\text{max}}=16$ was calculated with two-step method [10] and was presented as the constant $\varphi$ cross-section diagram with the segment of 5 °. Magnetic measurement was conducted on SY-937 veneer tester. The iron loss of P15/50 was collected at 90 °, 60 °, 30 °, 0 ° relative to rolling directions.

Table 1 The chemical compositions of non-oriented silicon steel (wt%)

| C   | Mn  | Si  | Al  | N   | S   | P   | Sn  | Fe |
|-----|-----|-----|-----|-----|-----|-----|-----|----|
| 0.001 | 0.12 | 3   | 0.33 | 0.001 | 0.002 | 0.015 | 0.1 | Bal.

3. Results and discussion

3.1. The Recrystallization Texture under Different Annealing Temperatures
Figure 1 and Figure 2 are the constant $\varphi=45$ ° ODF cross-section for the plate annealed at 750 °C, 800 °C, 850 °C and 900 °C for 10min. The results show that the texture strength is higher at the fast roller side than at the slow roller side, but recrystallization texture is basically the same under different annealing temperature. At the annealing temperature of 750 °C, the major texture component is $\gamma$ texture, while $\alpha$ texture is reduced. At 850 °C, texture component is gradually converged and major texture types are \{111\}<110> and \{111\}<112>.

At temperature higher than 900 °C, texture component tends to diverge. The intensity of \{111\}<110> and \{111\}<112> decrease and accumulate toward \{118\}, \{115\} and \{001\}.

The effects of temperature on $\alpha$ and $\gamma$ orientation line are shown in Figure 3 and Figure 4. It can be seen from Figure 3, the intensity of $\alpha$ texture at 750 °C annealing temperature is higher than that at other annealing temperatures. The peak was appeared around \{114\}<110> and \{111\}<110>. At annealing temperature of 850 °C, the peak appeared at \{118\}<110> for fast roller side, while for slow roller side the peak appeared at \{1115\}<110>. At 900 °C, no obvious change was observed for the texture intensity. As shown in Figure 4, \{111\}<110> and \{111\}<112> texture had the highest intensity at 800 °C. For sample annealed at 850°C and 900°C, the intensity of \{111\}<111> and \{111\}<112> texture are lower than that at 750 °C. The rolling speed ratio showed little effect on the annealing recrystallization texture for non-oriented silicon steel [11].
Fig. 1 The change of texture component with annealing temperature at the slow roller side.

(a) 750 °C  (b) 800 °C  (c) 850 °C  (d) 900 °C

Fig. 2 The change of texture component with annealing temperature at the fast roller side.

(a) 750 °C  (b) 800 °C  (c) 850 °C  (d) 900 °C

Fig. 3 The effect of temperature on α orientation line

(a) slow roller side  (b) fast roller side

Fig. 4 The effect of temperature on γ orientation line

(a) slow roller side  (b) fast roller side
3.2 Magnetism under different annealing temperatures

Recrystallization annealing has been performed at different temperatures and results of magnetic measurements are shown in Figures 5a and 5b. Figure 5b is the magnetic induction measured at different temperatures in different rolling directions. As can be seen from Figure 5, the magnetic properties obtained after recrystallization annealing at different temperatures are different. In the present experimental conditions, the iron loss is lowest at 800 °C. The influence of temperature on the magnetic induction is not significant. A low point was observed at 850 °C, and in other cases, the difference between the maximum and the minimum values is less than 0.1 T. The effect of rolling method on magnetic induction is also not significant. Comparison with synchronous rolling, asynchronous rolling has higher production efficiency and accuracy, therefore it can be used for the production of high-grade non-oriented silicon steel [12].

![Fig.5 The iron loss and magnetic induction under different annealing temperatures](image)

The magnetic property is closely related to the microstructure of the materials. It is not only depends on the atomic structure of the material, but also depends on the interaction between the atoms, such as crystal structure. The saturation magnetization of the ferromagnetic material and a saturated magnetic induction dependent on the material itself (composition) and the magnetic permeability and a coercive force is also determined by the material, but changes with the crystal texture and structure.

Recrystallization annealing is a process of using heat to activate high energy non-stable deformation texture to transform to low energy stable recrystallization texture. The recrystallized nuclear formed through some metal-structure during deformation and reflex needs to have enough size and enough orientation differences to the surroundings. Under asynchronous rolling conditions, there is a strong shear deformation. Under the same deformation conditions, the effect of asynchronous rolling is higher, which results in a large stress and strain gradients, making the distortion energy to increase in the cold rolled strip, when the recrystallization annealing occurs, the number of recrystallization grains with the driving force from such stored energy will significantly increase. From micro-structural mechanism, at the beginning of the recrystallization, some low defect density meta-structure will appear in the deformed matrix after reflex. If the grain boundary between meta-structure and deformed matrix is not the high movable large grain boundaries, it is not easy for recrystallization nuclear to grow. If the orientation of meta-structure is near the scattered zone in the transition zone, then the orientation gradient is bigger near the meta-structure. The big orientation difference between meta-structure and deformed matrix will help to form high movable large grain boundaries. Thus the meta-structure can quickly transform to recrystallized nucleus [13].

Generally, the grain boundary is the first nucleation site and apt to form a highly selective {111} texture. On the one hand, the vicinity of the grain boundary is subjected to the most severe strain and strain can give rise to the original grain boundary migration, thus sub-grain growth or aggregation occurs preferentially in the vicinity of the grain boundaries and high mobility large-angle grain boundaries are formed. On the other hand, due to the large deformation in the vicinity of the grain boundary, smaller dislocation cells formed and easily rotate in the same direction to form a strong {111} cold-rolled texture components which will give priority to the nucleation and easy to form
\{111\} recrystallization texture near the high energy grain boundary. The finer the grains, the stronger the \{111\} recrystallization texture. When the original grains is large, cold rolled grain was broken into several mosaic block and formed the shear zone at the grain boundaries. During annealing, it is beneficial to form \{110\} \{001\} nuclei but not the \{111\} \{110\} texture developed in the shear zone. The process of deformation texture to recrystallization texture is changed from high free energy anisotropic state to low free energy isotropic state. Based on oriented nucleation theory, preferred oriented nuclear forms and grows during the recrystallization process. In high energy zone, preferred orientation nuclear forms, then the non-deformed new nuclear grows by consuming the high energy matrix. Therefore, the high energy orientation increases for cold rolled sample during annealing, while low energy orientation decreases.

The texture component for asynchronous rolling is as same as that for synchronous rolling, however for alloy after the asynchronous rolling, asymmetric deformation formed in the deformation zone due to the presence of spinning rolling zone. A special change appeared in the type of texture and intensity for the metal with asymmetric metal deformational behaviour. In the spin rolling zone, the friction with reverse direction to the shearing stress will cause the different metal flow speed along the upper and lower surface of the spin rolling zone. Thus large shear force formed in the deformation zone will cause high shear strain. Different texture intensity forms along the fast and slow roller side. The orientation density of textures is higher along the slow roller side than that along the fast roller side. The formation of one time recrystallization is dependent on the crystal orientation. Recrystallization texture can easily form along \{111\}<112> orientation, but it is difficult to form along \{001\}<110> orientation. Because of the different crystal orientation in the cold rolled plate, recrystallization speed is significantly different. One time recrystallization texture has a strong relation with the \{111\}<112> orientation of the cold rolled texture. In the cold rolled texture component, there is a strong anti-gauss texture \{001\}<110>. After annealing the anti-Gauss texture weakens. The intensity texture decreases along both the fast and slow rolled side after annealing, while there is no significant change for the texture. The intensity of \{111\}<110> decreases and the intensity of \{111\}<112> increases. The different texture intensity along the fast and slow side of the roller is due to the stress difference during the asynchronous rolling process.

As shown in the ODF section view in Figure 2, for annealing temperature from 750 °C to 850 °C, \{111\} <112> texture forms, but with further increasing annealing temperature, due to the elimination of the residual stress of cold-rolled sample and the grain growth, the orientation density is increased on either the fast roller side, or slow roller side, and there are some other weak texture components appear, such as \{001\} <110>, \{001\} <HK0> etc. When the annealing temperature is further increased, the \{111\}<112> texture diffuses and disappears due to the growth and annexation of different orientation of grains, and further forms other textures. It is well known that for the influence of magnetic properties, the <001> direction has the highest magnetic conductivity, followed by the <110> direction, and the <111> direction is the worst. Therefore the \{111\} <112> texture formed by initial annealing does not increase the magnetic conductivity, or reduce the iron loss. With increasing annealing temperature, the elimination of the rolling stresses, the recrystallization and the appearance of some weak texture components lead to the decrease of iron loss. Magnetic conductivity decreased but not significantly. The lowest iron loss is achieved at 800 °C annealing temperature. The intensity of magnetic induction decreased slightly. when further annealed at 850 °C, because of the enhance of the\{111\}<112> texture, the emergence of a large number of unfavourable textures and the disappearance of favourable textures, the iron loss increases and the intensity of magnetic induction reaches to the minimum.

4. Conclusions
(1) Under asynchronous rolling conditions, with the increase of the recrystallization annealing temperature up to 850 °C, the texture gradually has more \{111\} <112> components; with further increase of temperature, the texture is dispersed and consists of strong\{118\} and \{1115\}, and \{001\} components.
(2) Temperature has significant effect on the iron loss, the lowest iron loss was found at 800°C. The influence of temperature on the magnetic induction is not obvious.

(3) In the different test temperature, the recrystallization texture component is basically identical at both fast and slow roller side, but at the fast roller side, texture strength is more than that of the slow roller side.

References
[1] Iwashita, S., Takezawa, M., Honda, T., et al. (2001) Changes in Domain Structure According to the Thickness of Non-oriented Electrical Sheets. Journal of the Magnetics Society of Japan, 25: 903.
[2] Kubota T, Fujikura M, Ushigami Y. Recent progress and future trend on grain-oriented silicon steel. J Magn Magn Mater, 2000, 215: 39.
[3] Huang, B.Y., Yamamoto, K., Yamashiro, Y., et al. (1999) Effect of the Cooling Condition on the Magnetic Properties of Non-oriented Silicon Steel Sheets. Journal of the Magnetics Society of Japan, 23: 1369.
[4] Zhang, Z.G., Liu, Y.D., Wang, F. (2010) The effect of annealing time on recrystallization texture and magnetic property of non-oriented silicon steel under asynchronous rolling. Transactions of Materials and Heat Treatment, 31(3): 69-72.
[5] Pei, W., Sha, Y.H., Zhao, R.Q., et al. (2012) Recrystallization Texture Development in Asymmetrically Rolled Non-oriented Silicon Steel. Journal of Northeastern University (Natural Science), 33(9): 1261-1265.
[6] Ma, L., Rong, Z., Xiang, L., et al. (2013) An Analysis on Structure and Inclusions in CSP Casting Slab and Hot Rolled Plate of High Grade Non-Oriented Silicon steel. Special SteelL, 34(4): 59-61.
[7] Xue, Y., Ma, L., Zhang, X.F., et al. (2015) Effect of normalizing process on texture in high grade non-oriented silicon steel. Transactions of Materials and Heat Treatment, 36(8): 151-154.
[8] Wang, L.T., Zhang, L., Shi, L.F., et al. (2017) Investigation of hot deformation behavior of high grade non-oriented silicon steel. Metallic Functional Materials, 24(3): 61-66.
[9] Sun, Q., Li, Z.C., Mi, Z.L., et al. (2016) Influence of annealing temperature on recrystallization behavior of a non-oriented electrical steel. Transactions of Materials and Heat Treatment, 37(03), 58-62.
[10] Liang, Z., Xu, J., Wang, F. (1981) Determination of ODF of polycrystalline materials from incomplete pole figures. IN: Proc 6th Int Conf on Textures of Materials. Tokyo: ISIJ. pp. 1259.
[11] Zhang, Z.G., Liu, Y.D., Wang, F. (2011) Effect of Temperature on Recrystallization Texture and Microstructure for non-oriented Silicon Steel under Asymmetrically Rolling Process. Advanced Engineering Materials, 194: 1314.
[12] Zhang, Z.G. (2008) The Study on the Texture and Property of Non-oriented Silicon Steel. Shenyang: Northeastern University.
[13] Tongtae, P. (2004) The heating rate on the non-oriented electrical steel texture formation. electrical steel, 3: 48.
[14] Matsuoks, S., Morita, M., Furukimi, O., et al. (1998) Effect of Lubrication Condition on Recrystallization Texture of Ultra-Low C Sheet Hot-Rolled in Ferrite Region. ISIJ International, 38(6):633.
[15] Mineo, M., Tetsuo, T., Kei, S., et al. (1999) Formation Mechanism of \{111\} Recrystallization Texture in Ferritic Steel. Iron and Steel, 85(10): 41.