Texture Improvement of 3% Si Non-Oriented Electrical Steel

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There are two important properties i.e. iron loss and magnetic induction influencing the quality of non-oriented electrical steel. Unfortunately, the low iron loss and the high magnetic induction are incompatible in the conventional metallurgy processes. In this study, the phosphorus-addition electrical steel is proposed to overcome the above problem. The effects of phosphorus-addition on magnetic properties, related microstructure and texture evolutions are analyzed. The results showed the P-added electrical steels have higher fraction of the Cube texture ({100}<001>) and a lower {111}<112> component compared with the data in non-P-added electrical steels. On the other hand, adding phosphorus in the electrical steel can also improve the mechanical property by solid solution strengthening and grains size refinement. The experimental results may help to realize the relationship between magnetic induction and texture evolution in P-added steels, and are useful in developing higher quality non-oriented electrical steels.

Keywords: Non-oriented electrical steel, Magnetic flux density, Texture, Phosphorus, Annealing process

1. INTRODUCTION

Electrical steels are functional and advanced materials used in motors, power generators and transformers for electrical applications. Due to global warming, some demands in reducing it include a decrease in energy consumption of electro-magnetic transformed machines. Giving considerable rise for highly efficient electrical steels, the most efficient solution to produce high quality electrical steel is to reduce its iron loss and increase its magnetic induction. Consequently, a lot of work and effort has been done on composition and metallurgic designs. In general, the iron loss of electrical steels can be reduced by adding Silicon (Si) and Aluminum (Al) in the melting-process(1), as these elements increase the electric resistivity and reduce the eddy losses caused by eddy current. Additionally, reducing the thickness of electrical steel also usually contributes to lower eddy losses for high-frequency motors applications. However, the two methods mentioned above will induce some problems, such as the reduction of iron fraction and an increase in the harmful microstructure and texture evolution caused by rolling which causes magnetic flux density to drop seriously. Therefore, there is a need to find ways that are suitable for both iron loss reduction and raising magnetic induction.

The appropriate magnetic properties in electrical steels can be accomplished by numerous metallurgy designs through the association of chemical composition and process controls. It has been known that the primary magnetic properties of electrical steel are texture dependent, and the desired magnetic induction can be achieved by texture controlling. Many studies have shown by adding small quantities of particular elements into non-oriented electrical steels with hot band annealing would improve the evolution of texture(2-4). Because these elements would segregate at grain boundaries during the hot band annealing, the elements prevent the nucleation of recrystallization near the original grain boundaries resulting in a decrease in the formation of (111) grains after cold rolling and final annealing. In the previous study, M. Godec et al. also found an increase of {001}<100> texture in the electrical steel with 0.05% Sn compared to steel without Sn(3). M. F. Rodrigues et al., furthermore, proposed the combination of 0.045% Sb addition and cold rolling reduction of 76% to acquire higher magnetic flux density and lower iron loss(5). Recently, an improvement of magnetic induction has been observed in the electrical steel with the addition of phosphorus (P)(6,7). The benefit of increased magnetic induction has attracted a lot of attention, since the phosphorus is inexpensive and phosphorus adding in the electrical steel is advantageous to increasing hardness. However, little research has been done to understand the development of texture in the P-added electrical steel, for this reason the raise of magnetic induction is still not clear.

The purpose of this study is to investigate the effect of phosphorus (P) addition on magnetic induction and its related texture development. A complete analytical technique has been demonstrated and the microstructures, texture evolutions of electrical steels with and without P-additions were examined by using an OM, X-ray and EBSD. The analysis presented in this study may help to clarify the correlation between phosphorus addition and texture changes in the non-oriented electrical steels.

2. EXPERIMENTAL METHOD

Two batches of 3% silicon-iron electrical steel with one having 0.2 wt% phosphorus content and the other with no P addition were used in this investigation. The chemical compositions of these steels are listed in Table 1. After continuous casting, the slabs of the two silicon steels were re-heated at a high temperature and subsequently hot rolled into a thickness of 2.3 mm. Hot-rolled bands with different phosphorus contents were continuously annealed in the N_2-purged furnace, and then cold rolled to 0.35 mm. The cold rolled sheets were then annealed at temperature ranging from 700˚C to 880˚C in an atmosphere of a mixture of H_2 and N_2 gases for recrystallization and grain growth. The heating cycles are illustrated in Fig.1. The values of Magnetic induction and iron loss were measured for annealed sheets using a single sheet tester along rolling and transverse directions.

Table 1 Chemical composition of the steels in this study (wt%)

Alloy	C	Si	N	S	p
Sample 1	<0.003	3	<0.003	0.0005	0.2 (P-Added)
Sample 2	<0.003	3	<0.003	0.0005	0.01 (Non-Added)

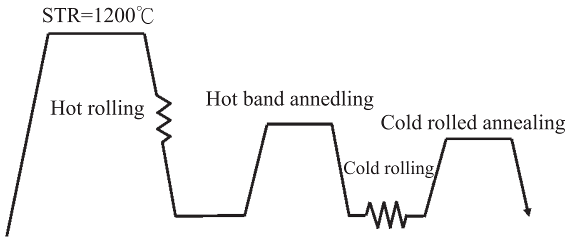

Fig.1. Schematic representation showing the heat treatment of electrical steels.

In this study, the microstructures of annealed hot-rolled and cold-rolled bands were observed using Optical Microscopy (OM), and the corresponding micro-textures of the same specimens were investigated by X-ray diffraction and Electron Backscatter Diffraction (EBSD). The area of observation for OM and EBSD analyses are located on the side of the specimen as shown in Fig.2(a). Differently, the area examined by X-ray diffraction is located on the top of the specimen, as Fig.2(b) shows.

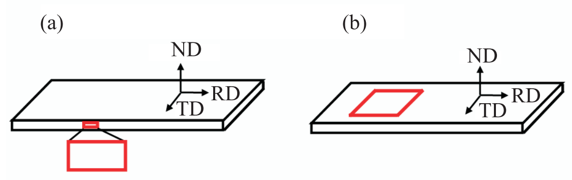

Fig.2. Schematic diagram of the analyzed location by (a) OM and EBSD (b) X-ray diffraction on the annealed hot-rolled and cold-rolled bands.

3. RESULTS AND DISCUSSION

The variation in the final annealing temperatures of the samples over magnetic flux densities with P-addition and non-P-addition is shown in Fig.3. The results indicate that magnetic induction of both steels increased with final annealing at temperatures ranging from 700˚C to 880˚C. Since the cold-rolled sheet annealed at lower temperatures has smaller-sized grains and some non-recrystallized structures, the residual stress in the structure of the steel resulted in the decrease of magnetic induction. It should be noted that another important result displayed in Fig.3 shows magnetic induction rises with phosphorus addition. The increase values of magnetic flux densities between the P-added and non-P-added steel sheet are in the range of 0.002-0.015 t. Hence, the P-addition in electrical steel could improve the magnetic induction.

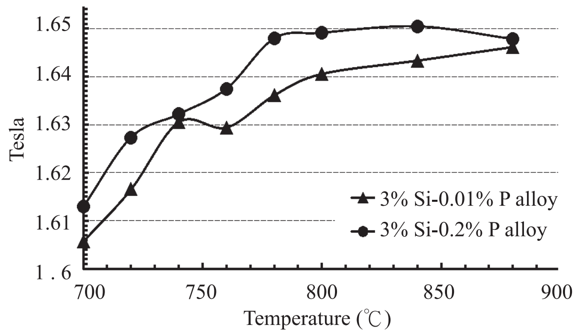

Fig.3. Effect of phosphorus addition and final annealed temperature on magnetic flux density of electrical steels.

Figure 4 shows that the microstructure and micro-texture of annealed hot-rolled bands in P-added (Fig.4(a)) and non-P-added (Fig.4(b)) steels. It was observed that the grain size decreases slightly in the steel with phosphorus addition. This is because P segregates at grain boundaries and restricts the grain growth during recrystallization, the average grain size of the steel is smaller. Furthermore, the micro-textures of these two steels are also different. As shown in Fig.4(b), the steel without P-addition has an apparent

{110}<112> component compared with P-added steel. According to the fundamental studies[2,3], some elements could segregate at grain boundaries due to energy reduction varying with the characteristics of grain boundaries. Consequently, the distribution of segregated elements would influence the crystallographic orientation and texture after the final annealing process. Similarly, the results shown in Fig.4 demonstrate the P segregation plays an important role in texture evolution. After hot-rolled annealing, the different texture may affect texture development at sequent cold-rolled annealing.

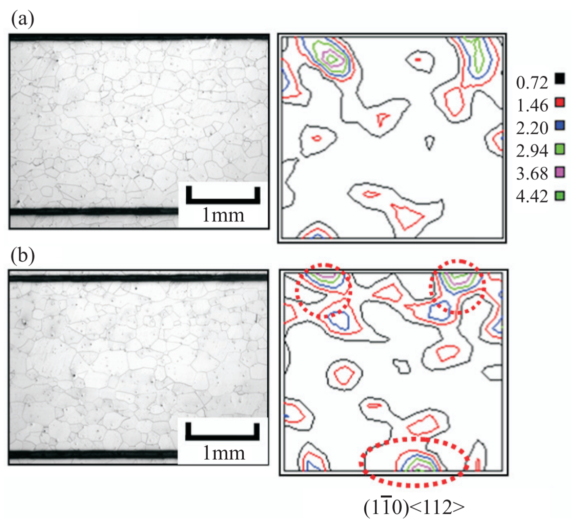

Fig.4. OM micrographs and texture analyses of annealed hot-rolled bands in (a) P-added and (b) non-P-added steels.

Figure 5 shows the micro-textures of the annealed cold-rolled sheets which were heated at 760°C for 60 s in the non-P-added (Fig.5(a)) and P-added (Fig.5(b)) steels. Obviously, the major texture of these two steels are close to (001) [110] components in the early stage of the recrystallization. However, it can be found that the steel with phosphorus addition has a higher fraction of the Cube texture ({100}<001>) compared with the texture in non-P-added steel. The difference in the texture is important evidence in demonstrating that the phosphorus addition in electrical steel can influence its texture evolution during the whole processes and increase the magnetic induction.

In addition to the findings of the micro-texture at the early stages of recrystallization, the texture of the annealed sheets heated at 840°C for 60 s were also observed, as illustrated in Fig.6. It shows the intensity of the {111}<112> component is lower in the P-added steel as compared with non-P-added steel. Since {111}<112> component seriously degenerates magnetic induction in the electrical steels, the lower {111}<112> texture may contribute to the increase in the magnetic induction with phosphorus-addition as shown in Fig.3. The reason for this texture optimization may be explained by previous studies that the phosphorus segregated at the initial hot-annealed grain boundaries can prevent the nucleation of recrystallization with {111} orientation near the original grain boundaries[4]. Therefore, according to the above observation of texture evolution, it can be concluded that the texture of steel with phosphorus content is favorable compared with non-P-added steel.

In order to realize more detailed texture evolution, the EBSD orientation maps of the annealed cold-rolled

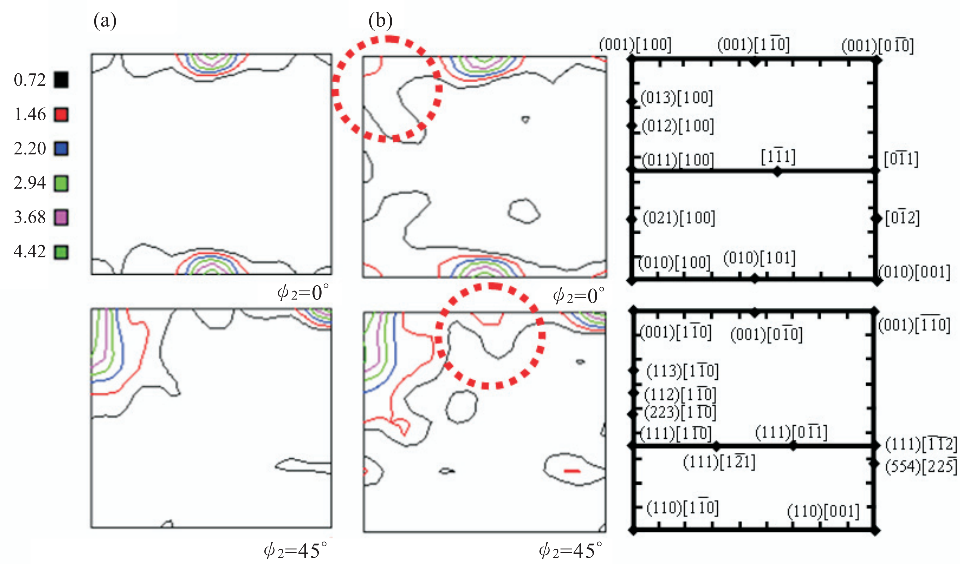

Fig.5. ϕ 2=0 and 45° ODFs of (a) non-P-added and (b) P-added steels at the mid-plane of sheets after cold-rolled annealing at 760°C for 60 s.

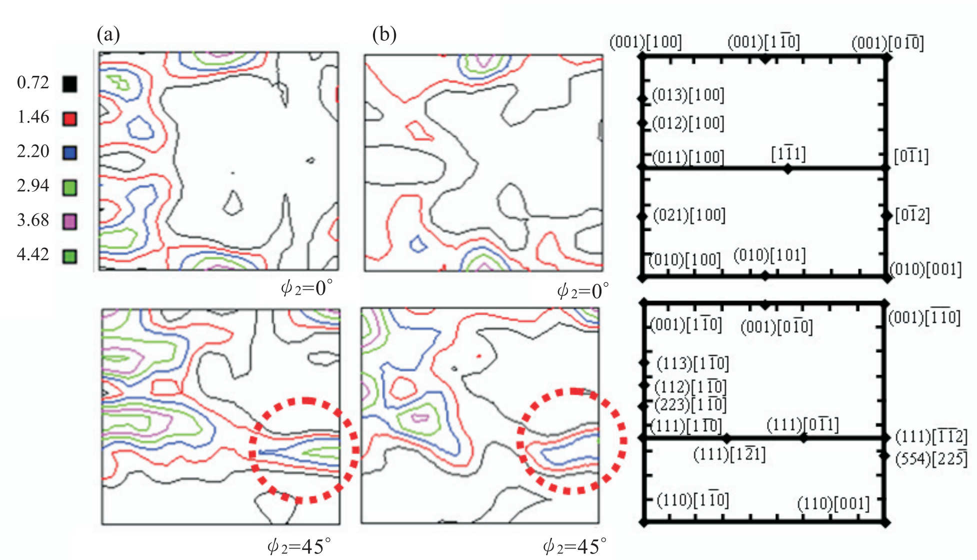

Fig.6. ϕ 2=0 and 45° ODFs of (a) non-P-added and (b) P-added steels at the mid-plane of sheets after cold-rolled annealing at 840°C for 60 s.

bands of these two steels have also been observed in this study. Figures 7 and 8 show the orientation maps of cold-rolled sheets annealed at 760°C for 60 s of non P-added and P-added steels, respectively. In the orientation maps, the grains which rolling and normal directions are all parallel to <100> can be considered as the favorable texture, also called Cube texture in electrical steels. In Figure 7, it is observed that the steel without P-addition has extremely less Cube texture after cold-rolled annealing at 760°C. However, in Fig.8, a small amount of Cube texture can be observed in the P-added steel after annealing at the same temperature. Therefore, the results in the orientation maps again confirm the observation mentioned above that the optimized texture of the electrical steel can be obtained by adding phosphorus.

Since the examination of texture changes during the annealing process had been well known via this research, the influence of P-addition on yield strength and iron loss have also been investigated in the present study. Figure 9 shows the microstructure and corresponding yield strength of cold-rolled sheets heated and soaked at 880°C for 60 s of non-P-added and P-added steels. The result indicated that the effect of P-addition played an important role on grain size refinement due to the restriction of grain growth after the final annealing process and contributed to the increase in yield strength. Recently, there has been a great demand for large size high-speed motors and Interior Permanent Magnet Synchronous Motors (IPMSM), the electrical steels used for such motors need enough strength to avoid fracture(8-10). Because of the centrifugal force acting on a rotating motor is proportional to the radius of a motor and increases proportionally to the square of the speed of a motor, furthermore the magnet embedded inside the rotor core of IPMSM also increase the loading of electrical steel. Hence, electrical steels with higher strength must be developed to prevent deformation or

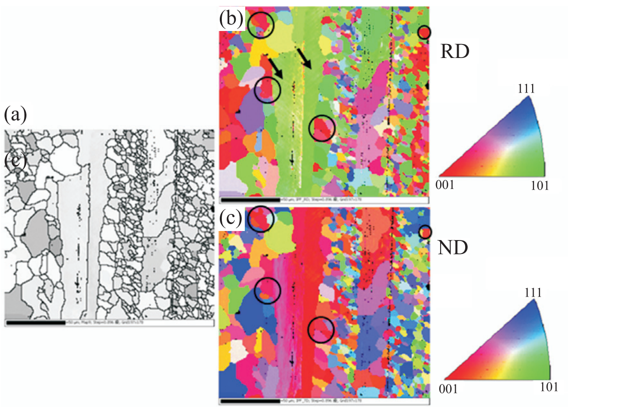

Fig.7. Orientation map of the annealed cold-rolled sheet of non-P-added steel heated at 760°C for 60 s.

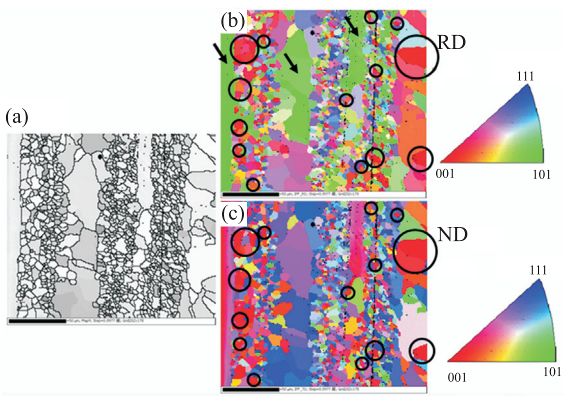

Fig.8. Orientation map of the annealed cold-rolled sheet of P-added steel heated at 760°C for 60 s.

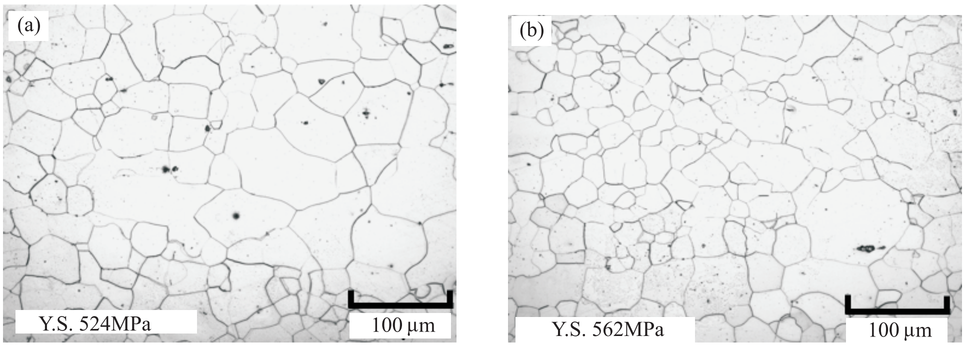

Fig.9. Micrographs of annealed cold-rolled sheet of (a) non-P-added and (b) P-added steels heated at 880°C for 60 s.

fatigue fracture due to the rotational high speed of motors and to ensure the durability of the rotor cores. The result presented in this paper shows that the yield strength of electrical steel can be improved by adding phosphorus owing to the causes of solid solution effect and grain size refinement. In addition, the iron losses of cold-rolled sheets of two alloys annealed at temperatures ranging from 700˚C to 880˚C with different yield strengths were also measured as shown in Fig.10. The result shows the specimen with P-addition has lower iron loss compared with the non-P-added sample at the same yield strength. Hence, it can be found that adding phosphorus in the electrical steel is an appropriate solution that can improve magnetic induction, lower iron loss, and increase yield strength.

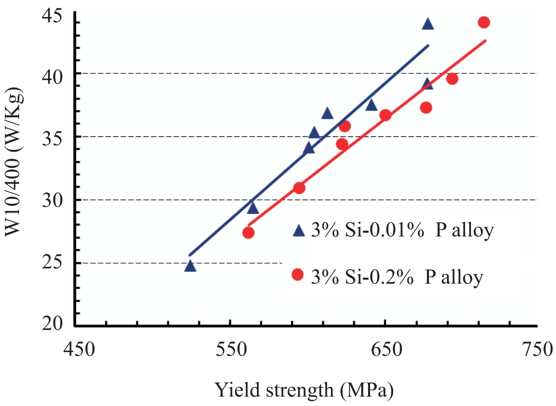

Fig.10. Relationship between yield strength and iron loss of P-added and non-P-added steels.

4. CONCLUSIONS

1. The effect of phosphorus addition to 3% silicon steel on texture evolution has been investigated. The results show textures can be optimized by adding phosphorus. A higher fraction of the Cube texture ({100}<001>) has been observed in the P-added steel and the {111}<112> component, which is harmful to magnetic properties can be suppressed after the annealing process.
2. The microstructure, yield strength and iron loss of annealed cold-rolled sheets have also been examined in this study. It was found that the yield strength increases with phosphorus addition as a result of grain size refinement. In addition, the iron loss of P-added steel was lower compared with steel without P-addition with the same yield strength. The results presented in this study are helpful to ascertain the effect of phosphorus addition on both magnetic and mechanical properties.

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