Texture Effect on Magnetic Properties by Alloying Specific Elements in Non-grain Oriented Silicon Steels

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The effect of texture on magnetic properties by adding specific elements of tin, antimony and boron was investigated. Texture factor was defined as the ratio of the sum of cube and Goss textures to $\gamma$ fibre. Tin and antimony showed larger effect in enhancing grain size than boron for both hot rolled and cold rolled bands. Texture factor increased with an increase in grain size; that is, grain size effect on texture factor appeared larger for the addition of tin and antimony than for boron. Both tin and antimony showed large volume fractions of cube and Goss textures but low volume fraction of $\gamma$ fibre compared to boron. The effect of texture factor on core loss was larger for tin and antimony added steels than for boron added steel. Magnetic flux density increased proportionally with the texture factor and the effect of texture factor on magnetic flux density was also greater in tin and antimony added steels than in boron steel.

KEY WORDS: texture volume fraction; texture factor; core loss; magnetic flux density.

1. Introduction

The magnetic behavior of non-oriented electrical steels is controlled primarily by several microstructural features of texture, grain size, and impurity. Texture or crystallographic preferred orientation is produced as a consequence of grain boundary migration during recovery, recrystallization, and grain growth which are affected by anisotropy in energy, mobility and stored energy. The (100) and (111) components are very important factors that affect the magnetic flux density of silicon steels, that is, high intensity of (100) components improve magnetic properties but (111) components deteriorate them. The (100) and (111) components are developed by precise control of composition and/or manufacturing processes, and so magnetic properties of materials are improved by reducing core loss and improving permeability, particularly high magnetic flux density. Agreeably, the magnetic properties are very dependent upon chemistry and process variables which control texture and grain size. In fact, non-oriented electrical steels are aimed to get close state to non-texture, which would guarantee maximum isotropy of magnetic properties. It is more advantageous to obtain a (100)$\langle uvw \rangle$ structure. It is obvious that approaching the non-textural state is realized by a strong decrease of the (111) texture component and by significantly increasing other texture components, especially (100) and (110).

Antimony is known to be an efficient element in improving the magnetic properties of electrical steels because the (100)$\langle uvw \rangle$ texture can be improved when it is added to steel. It segregates on grain boundaries and selectively affects the growth of recrystallized ferrite grains impairing the growth of (111) grains. The number of (111) grains in a rolling plane is diminished with the addition of antimony.

Tin has a similar characteristic to antimony in silicon steels. It also improves the magnetic properties of silicon steels by obtaining the desired texture, and it prefers to segregate along the grain boundaries. In 1979, Nippon Steel found that fine AlN particles were precipitated during slab reheating by adding 0.002–0.004% boron due to the preferential formation of BN at that time, while coarse AlN precipitates were found to form in the nucleation of BN. Furthermore, (111) texture intensity also decreases with an increase in the pronounced (110) $\langle 001 \rangle$ texture.

In the present work, the effects of tin, antimony, and boron on the texture of high grade non-oriented silicon steels were investigated based on experiments combining the optimum control of processing parameters. In particular, the effect of texture on magnetic properties by adding these elements was evaluated and thus the relationship between texture factor and magnetic properties was investigated. The texture factor was defined as the ratio of the sum of cube and Goss textures to $\gamma$ fibre.

2. Experimental Procedure

Chemical compositions obtained from vacuum melted ingots are shown in Table 1. Ingots were hot rolled to 2.6 mm, annealed at 1 000°C for 3 min, cold rolled to 0.35 mm, and finally annealed at 1 000°C for 3 min in a mixed gas of 30% H$_2$ and 70% N$_2$. Magnetic properties were measured for five specimens each steel using a single sheet tester. The measurement of core loss ($W_{15/50}$) was conducted using the frequency of 50 Hz at the induction of 1.5 T. The magnetic flux density ($B_{50}$) was measured at the magnetizing force of 5 000 A/m. Test data of both core loss and magnetic flux density obtained from longitudinal and transverse to rolling.
direction were averaged. Microstructures were analyzed on the cross-section perpendicular to the rolling direction of the samples. (110), (200) and (211) pole figures were taken by X-ray diffractometer only from the surface layer of the specimens for texture analysis. The orientation distribution function (ODF) \( f(g) \) was calculated from the pole figure data. Quantitative texture analyses for the volume fraction and orientation fibres were carried out by using Textools software in which texture volumes for ideal orientations and fibres were obtained from the ODF calculation.

3. Results

3.1. Grain Size

Figure 1 illustrates optical micrographs for an annealed steel specimen. Table 2 lists grain sizes of materials after hot rolling, cold rolling, and annealing. Alloyed steels B, C and D have smaller final annealed grains than those of non-alloyed steel A. Of these three alloyed steels, boron added steel C has the smallest grain size. Also of note is that steels having larger grains after hot rolling also have larger grains after recrystallization annealing. However, steels B and D have very similar grain sizes after each process. This means that both tin and antimony do indeed have very similar effects on recrystallization grain growth. Steels containing tin and antimony, comparing to the non-alloyed steel, have small grain sizes, which means that these elements hinder grain growth during recrystallization by segregating in grain boundaries but they are not as restricted as boron.

3.2. Magnetic Properties

Table 3 shows the magnetic properties of final annealed sheets. The antimony added steel D has the highest flux density of \( B_{50} \) and is similar to the tin added steel B. Their improvement of magnetic flux densities compared to the non-alloyed steel A is not noticeable. The iron losses of steels A, B and D are very close to each other at 2.3–2.4 W/kg. But the boron added steel C shows a significant increase of core loss and decrease of magnetic flux density compared to the other steels. This result indicates that boron is fairly detrimental to magnetic properties.

3.3. Texture

The crystal orientation distribution was analyzed with a tolerance degree of 15° for each texture and fibre, as illustrated in Fig. 2. It is not easy to discern the differences with the naked eyes, and it requires a rigorous numerical analysis to ascertain the volume fractions of constituent fibres. Calculation of texture volume fraction based on ODFs obtained from the experimental data was well established by ResMat. Among various texture components, cube, Goss and \( \gamma \) textures are strongly related to magnetic properties. In particular, \( \eta \) fibre is routinely analyzed in electrical steels because it shows cube intensity at \( \Phi=0° \) and Goss intensity at \( \Phi=45° \) in orientation distribution intensity as functions of \( \Phi, \varphi_1 \) and \( \varphi_2 \).

The present work adopted the texture factor for the correlation of texture with magnetic properties. Texture factor is defined as the ratio of the sum of cube texture and

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\text{Table 1. Chemical compositions of test steels.}
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| Steel | Si  | C   | Mn  | Al  | S   | N   | Sn  | Sb  | B   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| A     | 2.01| 0.0025 | 0.30 | 1.00 | 0.0007 | <0.001 |     |     |     |
| B     | 2.00 | 0.0033 | 0.30 | 0.98 | 0.0008 | <0.001 | 0.10 |     |     |
| C     | 2.01 | 0.0003 | 0.30 | 0.98 | 0.0008 | <0.001 |     | 0.0043 |     |
| D     | 1.99 | 0.0027 | 0.30 | 0.98 | 0.0008 | <0.001 |     | 0.076 |     |

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\text{Fig. 1. Example of optical microstructures of hot rolled and cold rolled-annealed steels; (a) hot rolled and (b) cold rolled and annealed steel B.}
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\text{Table 2. Mean grain size after hot and cold rolling.}
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| Steel | Hot rolled | Cold rolled and Annealed |
|-------|------------|-------------------------|
|       | Mean size (\( \mu m \)) | No.of grains | Mean size (\( \mu m \)) | No. of grains |
| A     | 167.9      | 299        | 141.7                 | 184              |
| B     | 163.3      | 265        | 130.6                 | 182              |
| C     | 148.6      | 291        | 111.8                 | 197              |
| D     | 161.5      | 287        | 126.2                 | 201              |

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\text{Table 3. Magnetic properties of annealed steels.}
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| Steel | Magnetic Flux Density\( (B_{50}) \), Tesla | Core Loss\( (W_{1200}) \), W/Kg |
|-------|--------------------------------------------|---------------------------------|
|       | Longitudinal | Transverse | Mean | Longitudinal | Transverse | Mean |
| A     | 1.696       | 1.677       | 1.682 | 2.197         | 2.462       | 2.330 |
| B     | 1.709       | 1.672       | 1.691 | 2.240         | 2.524       | 2.391 |
| C     | 1.696       | 1.659       | 1.677 | 2.557         | 2.810       | 2.683 |
| D     | 1.726       | 1.677       | 1.701 | 2.255         | 2.484       | 2.370 |
Goss texture to γ fiber, not the ratio of cube texture only to γ fiber, since Goss texture together with cube texture is also efficient for improving the magnetic properties of electrical steels. γ fiber was represented as the sum of four major orientations of (111)[110], (111)[121], (111)[011] and (111)[112]. In Table 4 are revealed the volume fractions of textures of cold rolled and annealed sheets. Cube texture shows a much larger volume fraction than Goss texture but is much lower than γ fibre. The steel C containing boron has the lowest sum of cube and Goss texture fraction and the highest γ fiber fraction. While steels B and D have much lower fractions of γ fiber and higher cube and Goss textures than those of steels A and C. Steel D has the highest texture factor. The texture factor as shown in Table 3 increases in the order of D, B, A, and C steel. The tin or antimony containing steel has higher texture factor than the non-alloyed or boron added steel. The orientation distribution intensities of steels after annealing as a function of Φ (i.e. along the η fibre) and Φ, (i.e. along the γ fibre) are illustrated in Fig. 3. Steels B and D have higher intensities along η fibre direction as seen in Fig. 3(a) where the cube texture component of (001)[100] and Goss texture of (011)[100] are higher than steels A and C. which means that the former two steels are more easily magnetized. Figure 3(b) shows a strong γ fibre intensity at (111)[112] orientation at Φ=90° and a low intensity at (111)[110] at Φ=60°. Contrary to η fibre, steels A and C have higher intensities than steels B and D along the γ fibre direction, which also implies that these are less effective in magnetization.

4. Discussion

4.1. Grain Size Effect on Texture Factor by Alloy Addition

The addition of three alloying elements showed different

effects on grain size. Even for the previous stage of hot rolled bands, the boron added steel showed small grain size compared to other steels but tin and antimony alloyed steels showed larger and similar sizes. These characteristics displayed the same tendency in the cold rolled and annealed bands. The reason why boron steel has a smaller grain size is that boron is precipitated mostly in grain boundaries and thus precipitates restrict grain growth during recrystallization. However, steel containing tin or antimony revealed less difference in grain size in comparison with the non-alloyed steel, which means that both tin and boron are not very influential in the hindrance of grain growth. In order to ascertain the effect of grain size on texture the correlation of grain size with texture factor is shown in Fig. 4. From the viewpoint of simple grain size, the texture factor increases with an increase of grain size up to 130 μm and thereafter decreases. As mentioned prior, even though tin and antimony steels have a smaller grain size than non-alloyed steel, they have larger texture factors. Therefore, tin and antimony were effective in improving (100)[001] and (110)[001] textures but retarded the formation of (111)[uvw] orientations during grain growth stage of recrystallization.

4.2. Texture Factor Effect on Magnetic Properties by Alloy Addition

Tin added steel had the most cube texture followed by
antimony steel. These steels showed a higher Goss texture than boron contained steel. The volume of γ fibre detrimental to magnetic properties was favorably lower than both boron and non-alloy added steels. Therefore, the texture factor of the ratio of the sum of cube and Goss textures to γ fibre for tin and antimony alloyed steels appeared larger than that of boron steel. Both tin and antimony were effective in improving (100)[001] and (110)[001] textures but retarded the formation of (111)[uvw] orientations during the growth stage of recrystallization. Figures 5 and 6 illustrate the correlation between texture factor and core loss and magnetic flux density to ascertain the texture effect on such magnetic properties by alloying with tin, antimony, and boron. As shown in Fig. 5, boron added steel with a low texture factor showed a very large core loss but tin and antimony alloyed steels with a high texture factor showed quite low core loss. The correlation between texture factor and core loss does not seem to be exactly straight and linear but appears as core loss decreases with an increase in texture factor. As seen in Fig. 6 in which the relation between texture factor and magnetic flux density was illustrated, antimony addition shows the highest texture factor and thus the highest magnetic flux density of $B_{50}$. Tin added steel is next to antimony in terms of texture factor and magnetic flux density but boron added steel is very low. Consequently, the magnetic flux density, different from the case of core loss, is very much dependent upon texture factor. The relationship between these two factors shows a linear proportionality. That is, core loss increases proportionally with an increase in texture factor. This result obviously means that both cube texture and Goss texture are very effective in improving magnetic properties.

5. Conclusions

(1) Tin and antimony hinder grain growth but they are not as restricted as boron for both hot rolled and cold rolled bands. Texture factor increases with an increase in grain size at least up to 130 \( \mu m \) and thereafter decreases; that is, the grain size effect on the texture factor was larger for tin.
and antimony than for boron.

(2) Tin and antimony showed low iron loss but a high magnetic flux density compared to boron.

(3) Both tin and antimony showed high volume fractions of cube and Goss textures but a low volume fraction of γ fibre rather than boron, which means that tin and antimony are effective elements for developing cube and Goss textures but retarding γ fibre, thus improving texture factor.

(4) An increase in texture factor results in a decrease of core loss; that is, the effect of texture factor on core loss turned out to be larger for tin and antimony than for boron. In particular, magnetic flux density increases proportionally with texture factor and the effect of texture factor on magnetic flux density was great in tin and antimony alloyed steels compared to boron added steel.

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