# Development of a New Low-Loss and High-Permeability Non-Oriented Electrical Steel

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**Low iron loss of non-oriented electrical steel is the basic requirement for highly efficient electrical machine cores. Recently, in order to further improve the energy efficiency of motors, the demand of high permeability is also rising. However, these two magnetic properties are incompatible especially at high inductions. In this study, a new high-permeability fully processed silicon steel was developed, with an iron loss ($W_{15/50}$) of 2.90~3.20W/kg and a permeability ($\mu_{15/50}$) of 3400~3900 after stress relief annealing. The ideal magnetic properties of this new silicon steel are mainly achieved by appropriate reduction of alloy contents and better texture control with a higher fraction of [001]||RD (η-fibre) and a lower fraction of [111]||ND (γ-fibre). The experimental results are also useful in developing other high-grade non-oriented silicon steel.**

**Keywords: Non-oriented electrical steel, Permeability, Texture, Annealing process**

## 1. INTRODUCTION

Electrical steels are widely used as the core materials of electrical devices, such as motors, power generators, and transformers, and are the key material that determines their working efficiency(1). The essential requirement for electrical steel is low iron loss, which can remarkably enhance the performance of electrical machines. It is well-known that the production of low-loss grades of electrical steels is achieved by increasing alloy contents, such as silicon and aluminum. The electrical resistivity can be significantly raised by high alloy contents and thus it can reduce the eddy current loss. However, this would also lead to a negative effect on the saturation of magnetization. The magnetic flux density and permeability at high induction are accordingly decreased due to the reduction of ferromagnetic iron atoms.

Except for alloy design, another key factor for electrical steel is the crystallographic texture. An adequate texture control means that the magnetization behavior can be improved. Basically, a higher fraction of [001] ||RD (η-fibre) and a lower fraction of [111]||ND (γ-fibre) are the ideal composition of texture components for electrical steel. The former one is an easy axis of magnetization and the latter one is a hard axis of magnetization(2). Texture control is very important for obtaining the combination of magnetic properties. It is possible to reduce iron loss without deteriorating the permeability and flux density(3,4). The most common method to improve the texture after final annealing is to carry out hot band annealing before cold rolling. Many studies reported the effect of hot band annealing for texture control, such as coarse grains prior to cold rolling(5-8), coarsening of precipitates(9) and segregation at grain boundaries(10-12).

In recent years, the strong demands for reducing energy consumption drive the development of highly efficient silicon steels. A lower iron loss and higher permeability grade of non-oriented electrical steels can be one of the ideal solutions for improving energy efficiency of electrical motors. In the present study, a low-loss and high-permeability silicon steel was developed by careful control of alloy content (Si+Al) and optimized processing conditions for desired texture components. Both the effect of texture evolution and precipitates on the magnetic properties were analyzed and discussed.

## 2. EXPERIMENTAL METHOD

Table 1 shows the chemical compositions of two non-oriented electrical steel sheets used in this study. The common manufacturing process of non-oriented electrical steels is shown in Figure 1. The slabs were reheated at high temperature and were subsequently hot rolled. In order to further improve the magnetic properties, an adjusted intermediate annealing treatment (higher temperature and longer annealing time) was conducted for the hot rolled band of high permeability grade

**Table 1** Chemical composition of steels used in this study (wt.%)

| Product Grade | Si+Al | C | N | S |
|---|---|---|---|---|
| Conventional (C) | 2.2 | <0.003 | <0.003 | 0.0005 |
| High Permeability (HP) | 1.9 | <0.003 | <0.003 | 0.0005 |

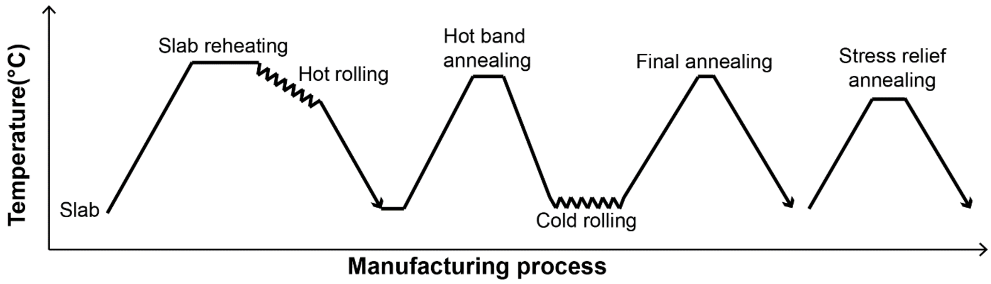


**Fig.1.** Schematic illustration for manufacturing process of electrical steels

before cold rolling. The cold rolled sheets of 0.5mm thickness were then annealed at temperatures ranging from 800 to 1000°C for recrystallization and final grain growth. In order to optimize the performance of motor cores, the electrical steel products after the punching process are usually subjected to stress relief annealing (SRA).

The magnetic measurements for the presented study were conducted with both Epstein frame method and single sheet tester (SST) by Brockhaus measurement systems MPG200. The Epstein data was obtained from the samples of appropriate manufacturing processes, which represented the typical properties of each grade. The magnetic flux density $B_3$, $B_{50}$, and $B_{300}$ were determined at magnetic field strength of 300, 5000, 30000A/m respectively. The iron loss $W_{15/50}$ and permeability $\mu_{15/50}$ were determined at a magnetic flux density of 1.5T and 50Hz. On the other hand, the deviations between conventional and high permeability grade at various final annealing treatments were measured by SST method. The value of each magnetic property obtained by SST method is the average of RD and TD measurement results.

The texture analysis of annealed cold-rolled sheets was measured on an X-ray texture goniometer (Bruker D8 DISCOVER). The $\varphi_2 = 45°$ section of the Euler space in orientation distribution function (ODF) is selected to show relevant orientations and fibres of each sample.

In order to characterize the distribution and size of precipitates, transmission electron microscopy (TEM) observations were performed on carbon extraction replicas. Samples were prepared using standard techniques and were investigated by using a TEM (JEOL JEM-2100Plus) with energy dispersive spectrometer (EDS). The composition and morphology of precipitates were verified.

## 3. RESULTS AND DISCUSSION

### *3.1 Magnetic properties and texture of high permeability grade*

The aim of this work is to develop a new grade of low-loss and high permeability electrical steel. However, the correlation between iron loss and permeability is kind of contradictory. In order to achieve low total loss, the most favorable way is obtaining large grain size and good texture control for decreasing hysteresis loss, and adding high Si+Al content to reduce eddy current loss.

On the other hand, permeability μ as the ratio of the flux density B and the magnetic field strength H, is much more complicated and harder to improve. The relationship between B and H ($B=\mu H$) is almost nonlinear, and thus the permeability strongly depends on the working point (magnetic field strength). At initial stage of magnetization (small magnetic field), the permeability is related to the mobility of magnetic domain wall As for the saturated stage, the texture and the alloy contents (less Si+Al is preferred) are of more concern for the rotation of magnetic domain. In this present study, the required permeability $\mu_{15/50}$ is close to the saturated stage and is therefore influenced by both factors. The optimum conditions for getting high permeability may be less hindrance such as coarse precipitates, good texture control, and adequate Si+Al content.

Accordingly, the key factors for acquiring low iron loss and high permeability simultaneously are appropriate alloy contents, adequate texture and precipitate control, since the iron loss can be compensated by grain size. Thus, the production of this new low-loss and high-permeability non-oriented electrical steel is based on low Si+Al content, and the manufacturing process comprises optimized hot-rolling process and intermediate annealing. Through higher temperature and longer time of intermediate treatments, large precipitates and coarse grain size before cold rolling can promote the final texture with more fraction of adequate component, [001]||RD (η-fibre), and less fraction of undesirable component, [111]||ND (γ-fibre). Accordingly, the improved texture results in an overall enhancement in magnetic properties, including lower iron loss, higher magnetic flux density and higher permeability.

The typical magnetic properties of conventional (C) grade and high permeability (HP) grade are listed in Table 2, and Figure 2 shows the corresponding texture of each grade. The high permeability grade has a significantly strong Goss (110)[001] component (relevant to η-fibre [001]||RD), and relatively weak γ fibre [111]||ND. This well-evolved texture contributed to extremely low hysteresis loss and thus the total loss could be lower than the conventional grade. The higher $W_{15/50}$ anisotropy of this new grade also indicates the

**Table 2** Typical magnetic properties of conventional and high permeability grades (before stress relief annealing)

| | Conventional grade | High Permeability grade |
|---|---|---|
| $W_{15/50}$ (W/kg) | 3.21 | 2.96 |
| $u_{15/50}$ | 1543 | 1794 |
| $B_3$ (T) | 1.366 | 1.393 |
| $B_{50}$ (T) | 1.721 | 1.756 |
| $B_{300}$ (T) | 2.040 | 2.069 |
| Anisotropy* ($W_{15/50}$) | -5.0% | -9.6% |

*Anisotropy = 100 × ($W_{RD}$-$W_{TD}$) / ($W_{RD}$+$W_{TD}$)

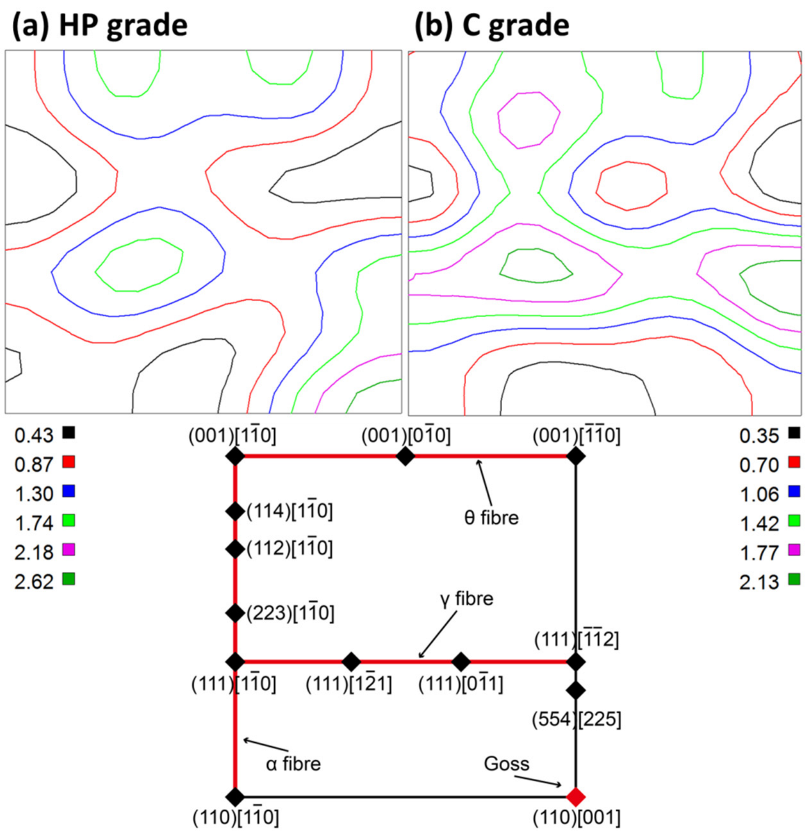


**Fig.2.** ODF section for $\varphi_2$ = 45° for (a) high permeability (HP) grade and (b) conventional (C) grade.

tendency of preferred texture.

In addition, the texture evolution during grain growth is very important for final permeability and magnetic flux density. In conventional grade, the γ fibre is slightly stronger than the new grade after low temperature annealing, but the intensity greatly increased after high temperature annealing (as shown in Figure 3), which is responsible for the deterioration of permeability and flux density. On the other hand, the texture of new high permeability grade is rather stable. The high intensity of the Goss component remained after high temperature annealing, while the γ fibre did not increase. Namely, the influence of grain growth on texture is very small in this new grade. The high permeability and magnetic flux density can be maintained with the same low iron loss, as indicated by Figure 4.

### *3.2 Features after stress relief annealing*

In order to annihilate the residual stress induced during the manufacturing process of motor cores, the non-oriented electrical steels are suggested to be subjected to the so-called stress relief annealing (SRA) treatment. This annealing treatment not only assures the recovery and improvement of magnetic properties of fully-processed silicon steel, but also is the essential process for semi-processed silicon steel, for which the final magnetic properties are achieved by considerable grain growth after stress relief annealing.

Another feature of the developed high permeability grade is that the iron loss and permeability would be significantly improved by SRA, which is similar to the behavior of semi-processed silicon steel. Figure 5 indicates the enhancement of $W_{15/50}$ and permeability $\mu_{15/50}$ of samples with various final annealing temperatures after stress relief annealing. It is interesting that the iron loss of high permeability grade came to the same value after SRA while only a few reductions occurred in the conventional grade at each annealing temperature. This improvement can be verified as the contribution of grain growth, which is closely related to the grain boundary energy and mobility. Through TEM observations as shown in Figure 6, one can find out that the precipitates in high permeability grade are obviously larger than those in conventional grade. That is to say, the retardation of grain growth caused by precipitates is rather weak in high permeability grade, and thus the grains size

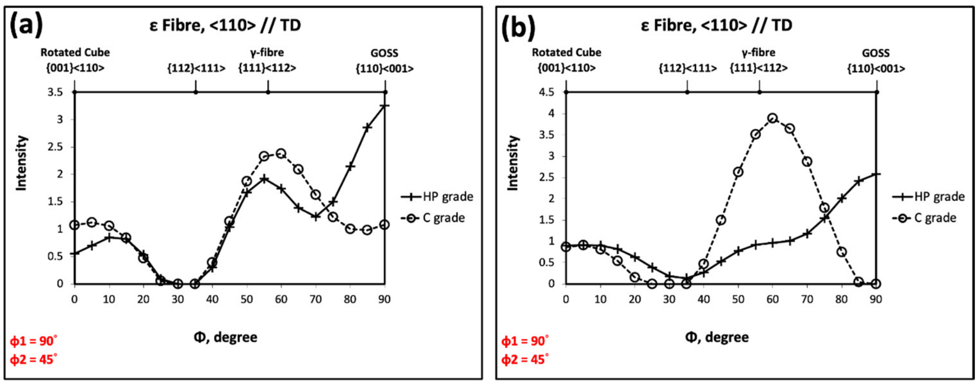


**Fig.3.** Texture analysis of ε fibre for samples annealed at (a) low temperature and (b) high temperature.

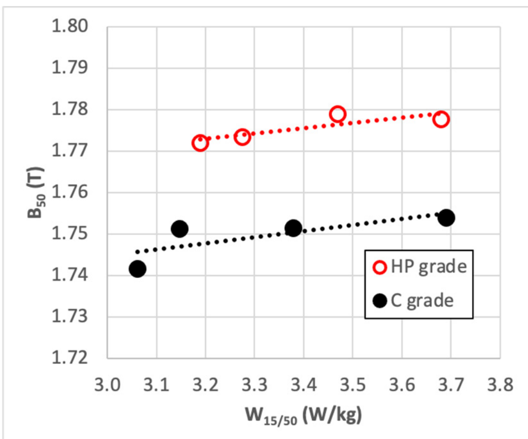


**Fig.4.** Iron loss $W_{15/50}$ and magnetic flux density $B_{50}$ of conventional (C) and high permeability (HP) grades

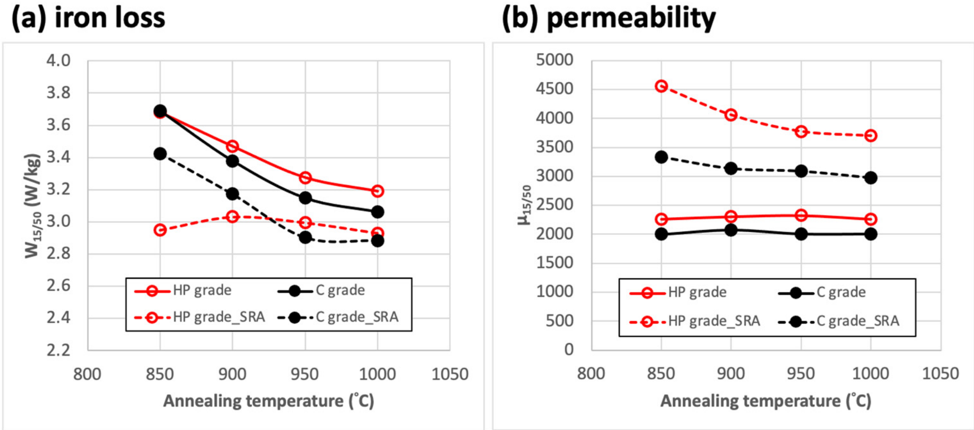


**Fig.5.** (a) Iron loss $W_{15/50}$ and (b) permeability $\mu_{15/50}$ versus final annealing temperature for conventional (C) and high permeability (HP) grades before and after stress relief annealing (SRA).

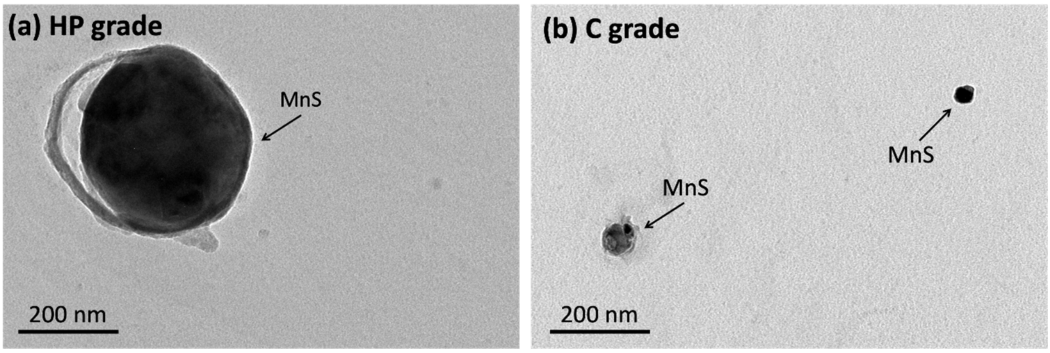


**Fig.6.** TEM observation of precipitates in (a) high permeability (HP) grade and (b) conventional (C) grade.

can increase to the optimum value after stress relief annealing. In contrast, the small precipitates in the conventional grade would result in a strong pinning effect on the grain boundary.

Moreover, the discrepancy in size of precipitates also has similar effect on the permeability, which represents the mobility of the magnetic domain wall during magnetization. Concerning the weak pinning effect of large precipitates, a notable increase in permeability of high permeability grade after stress relief annealing is shown in Figure 5(b). Especially for the sample of low final annealing temperature, the extraordinary raising of permeability was not only caused by large precipitates but also from the remarkable grain growth which reduces the area of grain boundary and enhance the magnetization behavior.

According to the above results, it was found that the optimum annealing parameter for high permeability grade is low final annealing temperature associated with stress relief annealing. The grain size can significantly increase and the final properties can simultaneously acquire low iron loss and high permeability.

## 4. CONCLUSIONS

A new grade of low-loss and high-permeability non-oriented electrical steel was developed in this study. Furthermore, the effects of crystallographic texture and precipitates on magnetic properties as well as iron loss and permeability have been verified. The appropriate texture control improved the whole magnetic properties by increasing the fraction of [001]||RD (η-fibre) component, and reducing the fraction of [111]||ND (γ-fibre) component. The slightly higher magnetic anisotropy also indicated the elevated preferred texture component in the new grade. With larger precipitates distributed in the matrix of the high permeability grade, the grain growth and magnetization behavior were facilitated and showed a significant enhancement after stress relief annealing.

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