Performance Analysis of Non–Oriented Electrical Steel with Optimum Texture for High–Speed Traction Motors

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Abstract. The magnetic properties of non–oriented electrical steel (NOES) vary significantly with respect to the microstructure and crystallographic texture of the final steel sheets, which, in turn, are highly dependent upon the thermomechanical processing parameters used during hot rolling, cold rolling and annealing. This paper performs an exploratory performance analysis of NOES for use in high–speed traction motors, emphasizing the importance of obtaining an appropriate crystallographic texture to achieve the desired magnetic properties by controlling the annealing temperature and holding time. A 3.2% Si NOES annealed at 860ºC for 24 hours after hot rolling can result in reduced core losses after cold rolling and final annealing. This material was chosen for the performance analysis of a laboratory scale high–speed, high–power traction motor (45 kW, 10,000 rpm) using finite element analysis (FEA). The motor using the NOES is compared to that using a commercially available grain–oriented electrical steel (GOES) to highlight the feasibility and advantages of NOES for high–speed motor applications. In addition, the motor performance using the NOES is compared to that using commercial NOES to understand the scope of improvement obtained by optimizing the microstructure and texture of the steel sheet.

1. Introduction

Soft magnetic core (electrical steel lamination) used in electric motors requires optimum magnetic properties, e.g. high permeability and low core loss, to render high performance of the motor. Non–oriented electrical steel (NOES) is widely used in electric machines, and the thermomechanical processing steps involved in steel sheet production significantly affect the microstructure/texture and the magnetic properties [1–3]. This paper performs an exploratory performance analysis of a laboratory produced NOES with optimum microstructure and texture [4] for application in high–speed traction motors. The electrical steel sheets were manufactured using conventional rolling and annealing processes but analysed at different annealing temperatures and holding times to understand the texture variation, and to obtain optimum magnetic properties. Based on the analysis, a 3.2% Si NOES after final annealing at 850ºC for 60 minutes was chosen for motor performance evaluation. An electromagnetic model of a 45 kW, 10,000 rpm laboratory scale high–speed, high–power motor was developed and used for analysis. First, the NOES is compared with a commercially available grain–oriented electrical steel (GOES) to understand the suitability and advantages over GOES for motor
applications. Motor performance characteristics in terms of rated torque production, maximum efficiency, rated core losses and operating speed range were obtained using finite element analysis (FEA). Furthermore, to understand the scope of improvement obtained from the optimized microstructure and texture, the motor performance using the NOES was compared with that using a commercially available NOES.

2. Non–Oriented Electrical Steel Processing and Analysis

Conventional manufacturing processes, i.e. hot rolling, annealing, cold rolling, and final annealing, were applied to the 3.2% Si NOES [4]. The steel was melted and cast into ingots, which were then reheated to 1050°C and hot rolled to a thickness of 20 mm in a reversing rolling mill in six passes. Further, to reduce the thickness to ~3.3 mm, a second hot rolling was applied under the same conditions. In order to remove surface oxides, the steel plates were then pickled in a hydrochloric acid solution. The hot–rolled plates were subsequently annealed at 860°C for 24 hours in argon–protected atmosphere and furnace cooled. The annealed plates were cold rolled to a final thickness of 0.35 mm and subsequently annealed again to obtain the final steel sheets. Final annealing was performed at various temperatures for different times to control the grain size and texture of the samples.

The textures of the steel were characterized using electron backscatter diffraction (EBSD) techniques in a field emission gun scanning electron microscope equipped with an EDAX Orientation Imaging Microscope (OIM) system. Using the grain orientation data, the grain sizes of the sample were calculated with the OIM software. The cross–section EBSD inverse pole figure (IPF) map of the final steel samples at different annealing temperatures and holding times and their corresponding textures are illustrated in Figure 1. AC and DC magnetization tests were performed on the final annealed steel strips using Epstein frame method to obtain the magnetic properties. It was found that the texture of the 3.2% Si NOES was optimized, i.e. a strong magnetically favourable θ–fibre (<001>//ND) was obtained, through a combination of a final annealing temperature of 750°C and a holding time of 60 minutes. This is because, annealing temperatures higher than 750°C resulted in preferred nucleation at shear bands, micro bands and fragmented grains which in turn increases the magnetically favourable θ–fibre and suppresses the magnetically detrimental γ–fibre. The steel strips after annealing under these conditions showed reduced DC core loss, the lowest AC core loss, and the maximum relative permeability. Thus, in this paper, the 3.2% Si NOES sample annealed at 850°C for 60 minutes is chosen for analysis.

![Figure 1. EBSD IPF maps showing the microstructure and texture of the final annealed steel sheet after final annealing at different temperatures and holding times: (a) 750°C for 180 minutes, (b) 850°C for 60 minutes, (c) 950°C for 30 minutes, (d) 1050°C for 10 minutes, (e) 1150°C for 2 minutes, (f) – (j) the corresponding textures [4].](image-url)
3. Structural and Target Performance Parameters of the High–speed Traction Motor
In order to emphasize the inherent advantages provided by the NOES material, a high–speed traction motor was chosen for analysis. A permanent magnet synchronous machine (PMSM) with the structural and target performance parameters defined in Table 1 was modelled using finite element method incorporating with different steel core materials for analysis. The electromagnetic model of the motor is shown in Figure 2. The net copper area, permanent magnet volume and the machine dimensions are kept constant for analysis. A rated current of 78 A rms/phase was applied to the machine and the performance characteristics thus obtained were analyzed in terms of rated torque production, maximum efficiency, rated core losses and operating speed range.

| Parameter            | Value     | Parameter            | Value     |
|----------------------|-----------|----------------------|-----------|
| Continuous Power     | 22 kW     | Stator Outer Diameter| 195 mm    |
| Continuous Torque    | 70 Nm     | Stack Length         | 75 mm     |
| Peak Power           | 45 kW     | Shaft Diameter       | 100 mm    |
| Peak Torque          | 150 Nm    | Air gap Length       | 0.5 mm    |
| Rated Speed          | 3,000 rpm | Magnet Material      | NdFeB 35  |
| Target Efficiency    | > 95%     | Wire Diameter        | 8.5 AWG   |
| Rated Current        | 78 A      | Total Magnet Weight  | 0.53 kg   |
| DC Bus Voltage       | 400 V     | Total Steel Weight   | 9.08 kg   |

Table 1. Structural and target performance parameters of the high–speed traction motor

Figure 2. Developed electromagnetic model of the high–speed traction motor used for analysis.

4. Comparative Performance Analysis of High–Speed Motor: The Studied NOES vs. GOES
The magnetic properties of the studied NOES are compared to that of a commercially available GOES as shown in Figure 3. Both the electrical steels under consideration have 3.2% of silicon and the thickness of each lamination sheet is approximately 0.35 mm. It can be observed from Figure 3(a), that for flux densities below 1.25 T, the core losses of the studied NOES are comparable with that of the commercial GOES along the rolling direction (RD), and for higher flux densities, the core losses are slightly higher for the NOES. Further, the variation of core losses with frequency under a fixed magnetic flux density of 1 T is illustrated in Figure 3(b), and it can be seen that the losses for both the electrical steels are very similar.

For the above–mentioned electrical steel properties, the electromagnetic model of the motor indicated in Figure 2 is analyzed at a rated current of 78 A rms/phase and a rated frequency of 400 Hz. It can be observed from Figure 4(a), that both the machines have the same torque–speed and power–speed characteristics since the NOES and GOES materials have very similar magnetization curves. However, the maximum torque obtained was 20.6 Nm lesser than the target due to limited flux density capabilities of the steel materials. Hence, for both NOES and GOES, the magnetization properties have to be improved to obtain the rated torque performance, or increasing the rated current of the motor would result in the required torque production. However, in such case, the motor copper losses will increase significantly, reducing the rated motor efficiency. Thus, further studies are required to analyze the most suitable solution for both NOES and GOES materials.
Furthermore, it can be seen from Figures 4(b) and (c), that the motor with the studied NOES results in 48.5% lower rated core losses than that with commercial GOES material which results in a 0.45% increase in the rated motor efficiency. This can be attributed to the fact that the NOES sample under

![Figure 3](image-url)

**Figure 3.** Comparison of magnetic properties of non–oriented and grain oriented electrical steels with 3.2% Si. (a) Core losses at different magnetic flux densities (with a fixed frequency of 125 Hz). (b) Core losses at various frequencies (with a fixed magnetic flux density of 1 T) [4].

![Figure 4](image-url)

**Figure 4.** High–speed motor performance characteristics with NOES and GOES materials. (a) Torque and power speed characteristics. (b) Core loss map of motor with GOES up to a maximum frequency of 1,200 Hz. (c) Core loss map of motor with NOES up to a maximum frequency of 1,200 Hz.
consideration has optimal grain size and texture as well as much smaller magnetic anisotropy in RD and TD as compared to GOES, which resulted in minimum eddy current and hysteresis losses. Furthermore, since the machine considered for analysis is a high–frequency, high–power motor, minimizing core losses in the electrical steel are the major contribution towards efficiency improvement [5]. The magnetic properties of NOES are highly dependent on the silicon content, cleanliness of the steel, the steel lamination thickness, grain size and crystallographic texture of the final lamination. Thus, for maximum magnetic flux density properties with minimally induced core losses, steel manufacturing process has to be optimized to obtain the required microstructure/texture with optimum performance characteristics [6].

5. Comparative Performance Analysis of High–Speed Motor: The Studied NOES vs. Commercial NOES

From the previous section, it can be seen that the motor with the studied NOES has better core loss characteristics and improved efficiency compared to the GOES counterpart. However, due to low magnetic flux density capability, the target torque performance of 70 Nm is not satisfied by the motor. In order to understand the inherent advantages of the studied NOES with optimized texture and grain size, the performance characteristics of the motor modeled in Section 2, is analyzed with the studied NOES and a commercially available NOES for the stator and rotor core material.

The torque– and power–speed characteristics obtained from the machines are illustrated in Figure 5(a). It can be seen that compared to the high–speed motor with commercial NOES, a 18.2% reduction in rated torque production, and a 14% reduction in output power capability are noticed for the motor with the studied NOES for a rated current of 78 A. However, due to the improved texture, the effective resistivity of the studied NOES is reduced, resulting in a 54.7% reduction in core losses when compared to the motor with commercial NOES. Furthermore, to match the torque rating, the current for the motor with the studied NOES material was increased from 78 A to 101 A. While this results in improved torque production, it directly reflects as increased motor copper losses and reduced efficiency. However, if the core loss improvement obtained from the studied NOES material is able to compensate for the increase in copper losses, the motor’s efficiency with both the steel materials should be comparable. It can be seen from Figures 5(b) and (c) that, for almost the same torque rating, the studied NOES has 2.3 times lesser core losses and 1.6 times higher copper losses than the commercial NOES resulting in very close motor efficiencies. Thus, it can be concluded that with optimum grain size and texture, the NOES can be modified to obtain maximum magnetic properties with minimal core losses.
Figure 5. Comparison of high-speed motor performance characteristics with commercial and studied NOES materials. (a) Torque and power speed characteristics for a 78 A current rating. (b) Rated motor efficiency and torque production at 78 A for commercial NOES and 101 A for studied NOES. (c) Core and copper losses at 78 A for commercial NOES and 101 A for studied NOES.

6. Conclusions
This paper performs an exploratory performance analysis of NOES materials for high-speed traction motors emphasizing the importance of obtaining appropriate microstructure/texture with desired magnetic properties by controlling the annealing temperature and holding time. It was found that final annealing at 850°C for 60 minutes resulted in magnetically favorable θ–fibre texture and an optimum grain size, which give rise to better magnetic properties. A laboratory scale high-speed high–power traction motor was chosen for performance evaluation using finite element analysis. It was found that for the studied NOES, it can produce the same torque and power as a commercially available GOES, with significantly reduced core losses. Furthermore, when compared to a motor with a commercial NOES, the studied NOES also resulted in significantly reduced core losses and comparable rated efficiencies for the same torque production, highlighting the scope of improvement obtained by optimizing the microstructure/texture of the steel sheets.

7. References
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