JSMPM

JOURNALS OF SUSTAINABLE MATERIALS PROCESSING AND MANAGEMENT
e-ISSN: 2821-2843

Vol. 6 No. 1 (2026) 84-90
https://publisher.uthm.edu.my/ojs/index.php/jsmpm

Effect of Si Content on Microstructure and Magnetic Properties of Electrical Steel

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DOI: https://doi.org/10.30880/jsmpm.2026.06.01.007

Article Info

Received: 25 February 2026
Accepted: 16 April 2026
Available online: 15 May 2026

Keywords

Electrical steel, magnetic properties, microstructure, grain size, equivalent Si

Abstract

Electrical steel (or silicon steel) is popularly used to manufacture motors and transformers. This paper presents the change in microstructure and magnetic properties of several electrical steels containing different amounts of silicon (Si). The samples were cut from different steel sheets, each 0.7 mm thick, for optical observation and magnetic testing. The investigation showed that the homogeneous microstructure of the steels consisted of ferrite with different grain sizes varying from 17 to 35 µm. The grain size increased with increasing Si content, in turn improving the magnetic properties of the studied electrical steel. Among the studied steels, the sample M4 containing 1.47 wt.% Si showed the best magnetic properties, including a coercivity (Hc) of 2.425 Oe, residual magnetism (Mr) of 0.0114 emu, saturation magnetization (Ms) of 7.11 emu and maximum energy product (BHmax) of 26947 MGOe. The obtained results will be useful and suggest to Vietnamese steelmakers to produce high-efficiency electric steel with proper chemical compositions.

1. Introduction

Currently, the demand for electrical steel has increased significantly due to requirements in transportation and electricity generation. The chemical composition of the steel is an essential factor because, by slightly modifying the phases, the total energy loss could be reduced, and the magnetic properties could be improved. It was found that adding a small amount of silicon (Si) to steel can significantly reduce hysteresis loss caused by eddy currents and increase the resistivity of steel [1-3]. This finding is crucial for electrical devices, marking a new era in the production of commercial Si steel. Since then, many grades of normal electrical steel with Si content below 1 wt.% and non-oriented grains have been widely used to produce electrical devices, such as motors and transformers, due to significant improvements in magnetic properties [3-6]. However, novel production routes have been developed; namely, the effect of grain size and crystallographic texture on magnetic properties of Fe-0.65 %Si non-oriented electrical steel produced by CSP process was investigated by Cong *et al.* [4]. An alternative strip casting was considered to directly produce as-cast strips with a thickness of 1-3 mm (close to that of conventional hot-rolled strips); thus, the hot-band normalizing step could be skipped in the manufacture of high-performance non-oriented electrical steels using this production route [7]. It is acknowledged that the microstructure and magnetic properties are important for increasing the quality of this steel. Based on the obtained microstructure, including the present phase and the grain size in the steel, the main properties of electrical steel can be predicted. This helps adjust production, develop new performance, and apply it effectively in the electrical field.

Currently, it has been confirmed that increased Si content increases electrical resistivity and permeability and decreases eddy-current losses, magnetostriction, and coercivity, while resulting only in a modest decrease in saturation magnetization. Researchers have attempted to increase the Si content in electrical steel, strictly control grain size, and develop non-oriented steel with stable magnetic properties to fulfil the increasing demand for use in electric cars and renewable energy [3,8,9]. For example, Kvackaj *et al.* focused on the magnetic properties of non-oriented isotropic electrical steel containing 3.5 %Si processed by conventional rolling at ambient temperature and progressive rolling, then undercooled in liquid nitrogen; the best magnetic properties obtained, as minimal core losses, were achieved after the electrical steel was rolled at cryogenic temperature, followed by subsequent annealing [8]. Leuning *et al.* studied the influence of production and processing on the resulting magnetic properties of a 2.4 %Si electrical steel [9]. However, high-Si-content steels cannot be produced as sheet solely by rolling despite the benefits of increasing Si content in electrical steel. As a notable challenge for sheet rolling of electrical steel (Fe-Si alloy), hot-rolled sheet products are generally limited to 4 %Si compositions [3].

In addition, the effects of annealing on the recovery of punching damage, microstructure, magnetic properties, and improvement of the electrical device's performance have been studied [10]. Scibisz *et al.* concluded that Si content, thickness, impurities, resistivity, permeability and domain structure of the steel significantly influenced core loss, which in the rolling direction were smaller than in the direction transverse to the rolling direction [11]. A study of the effect of thickness on power loss for non-oriented electrical steel sheets showed that a thickness of 0.50 mm caused higher losses than a 0.35 mm lamination thickness of steel [12]. Hunady *et al.*, who studied the effect of hot-rolling practice on the hot-band microstructure, reported that a hot-rolling process at temperatures of 880-920 °C produced a heterogeneous fine-grain microstructure; meanwhile, a temperature range of 830-870 °C created a more homogeneous microstructure and better magnetic properties for electrical steel [13]. The resulting information is valuable to the electric machine industry to produce high-efficiency electric machines. The latest improvements in the energy efficiency of these devices result in a positive impact on CO_2 emissions; a 1% improvement reduces emissions by several million metric tons [14]. Notably, Paltanea *et al.* investigated the influence of cutting methods for electrical steel lamellar on the normal magnetization curve, total energy loss, and magnetic permeability; waterjet cutting technology was confirmed to provide electrical steel with the best characteristics in terms of energy loss and magnetic permeability [15].

Despite recent studies, some key points, e.g., compositions and Si content, still require further information. In the production of electrical steel, the Si content is a very important parameter; therefore, an optimal Si addition should be carefully determined for a specific electrical device. To supplement information for the domestic steelmaking manufacturer, this paper investigated the changes in microstructure and magnetic properties with the Si content in some electrical steel grades.

2. Experimental Procedure

The specimens were cut from electrical steel sheets, approximately 0.7 mm thick, provided by an electrical device fabricating company. Subsequently, the specimens were investigated without any treatment (such as deformation or annealing). The chemical compositions of the steels were determined using optical emission spectrometry (Spectromaxx LMF08). For microstructural observation, specimens were mounted in epoxy resin, ground using abrasive papers (grit sizes ranging from 100 to 1500), and polished with chromium oxide particles and an oily lubricant. The specimen was etched using an aqueous 5 vol.% Nital solution. The microstructures of the steel sheets' cross-sections along the rolling direction were observed by optical microscopy (Olympus GX53). The grain size of the steel was defined as the average diameter determined by the mean linear intercept method on micrographs. Grain size was measured using the linear intercept method according to ASTM E112, in which a line was superimposed on the optical microstructure. The true line length was divided by the number of grains intercepted by the line. This gave the average length of the line within the intercepted grains. The average grain size of the steel was determined from five measurements. The hysteresis curve of the steel was measured by a vibrating sample magnetometer (MicroSense EZ9), which used the sample with a dimension of 10×10 mm. These measurements were conducted at room temperature in the direction parallel to the surface of the steel, and the applied magnetic fields were varied from 0 to 15 kOe. Based on these curves, magnetic properties, including the coercivity (Hc), residual magnetism (Mr), saturation magnetization (Ms), and maximum energy product (BHmax) were determined.

3. Results and Discussion

Table 1 presents the chemical compositions of the studied steel. Carbon was the most detrimental influence, worsening magnetic properties as carbides precipitated, increasing energy loss [16]. To solve this problem, the C content is typically kept at an ultra-low level, and annealing the steel in a decarburizing atmosphere can be used for electrical steel containing higher C. Clearly, all the steels contained a low C content - an element that negatively impacts the magnetic properties of electrical steel. In general, hysteresis and eddy current losses decrease with increasing Si content; the reduction in eddy current loss is primarily due to the increase in resistivity as Si is added to electrical steel. Among the 4 steel samples, steel M1 contained a very low Si content of 0.037 wt.%, indicating that the steel's composition was the same as that of the low-C steel. Other steels (M2-M4) contained a higher Si, so these steels were expected to have better magnetic properties. In electrical steel, not only Si but also several elements play positive roles in magnetic properties. For example, aluminium (Al) increases the resistance of electric steels and hinders the coalescence of grains during the annealing process, so this element is usually added together with Si, resulting in improved magnetic properties. Thus, Hunady *et al.* used the concept of equivalent Si calculated through equation (1) to evaluate the quality of electrical steel [13]. The calculated results are listed in Table 1. Again, the calculated Si-eq in steel M1 was very low, confirming that the effects of Si and other equivalent Si elements have been neglected.

$$\mathrm{Si-eq} = \%\mathrm{Si} + 2 \times [\%\mathrm{Al}] - 0.50 \times [\%\mathrm{Mn}] + 2.92 \times [\%\mathrm{P}] \quad (1)$$

Table 1 *Chemical compositions of the investigated steels (wt.%)*

	C	Si	Mn	Al	Ni	Cr	S	P	Si-eq
M1	0.073	0.037	0.330	0.042	0.016	0.016	0.013	0.025	0.029
M2	0.009	0.740	0.300	0.001	0.010	0.016	0.011	0.011	0.624
M3	0.037	0.800	0.150	0.199	0.005	0.026	0.002	0.004	1.135
M4	0.032	1.470	0.751	0.200	0.006	0.027	0.004	0.003	1.504

In a metallurgical context, there is a relationship among magnetic properties, Si content, alloying elements, and microstructure. According to Elgamli *et al.*, the microstructural characteristics of electrical steels were important for investigating the impact on magnetic behavior and performance [16]. Increasing grain size was found to reduce magnetic properties and core loss; a proper grain size for optimal magnetic properties was in the range of 26-30 μm [4]. Figure 1 shows optical images of the steels, which had microstructures consisting only of the ferrite phase. In the practical annealing conditions, the slow cooling rate is applied, so it can be confirmed that the observed grains were equiaxed polygonal ferrite grains. However, the ferrite grains were not similarly distributed. Except for steel M3, heterogeneous microstructures were seen in steel M1, M2, and M4. Abnormally large grains were observed to be embedded in smaller ones in these steels, resulting from the emergence of small grains during secondary recrystallization, in which grain growth (or migration of grain boundaries) is strongly influenced by temperature. Because the driving force for grain growth is usually very small, significantly coarsened grains are often found at high temperatures. Among those, the steel M4 had very large grains (35 μm on average) and a markedly different grain-size distribution. This phenomenon might be attributed to high Si content and prior annealing processes. As the annealing temperature increased, the grain size of the steel sheet gradually became larger; especially, the grain size increased drastically to coarser ones [4]. Thereafter, this undesired phenomenon created a heterogeneous microstructure in the electrical steel, affecting magnetic domains by reducing the number of pinning sites and domain boundaries, and finally negatively impacting the magnetic losses.

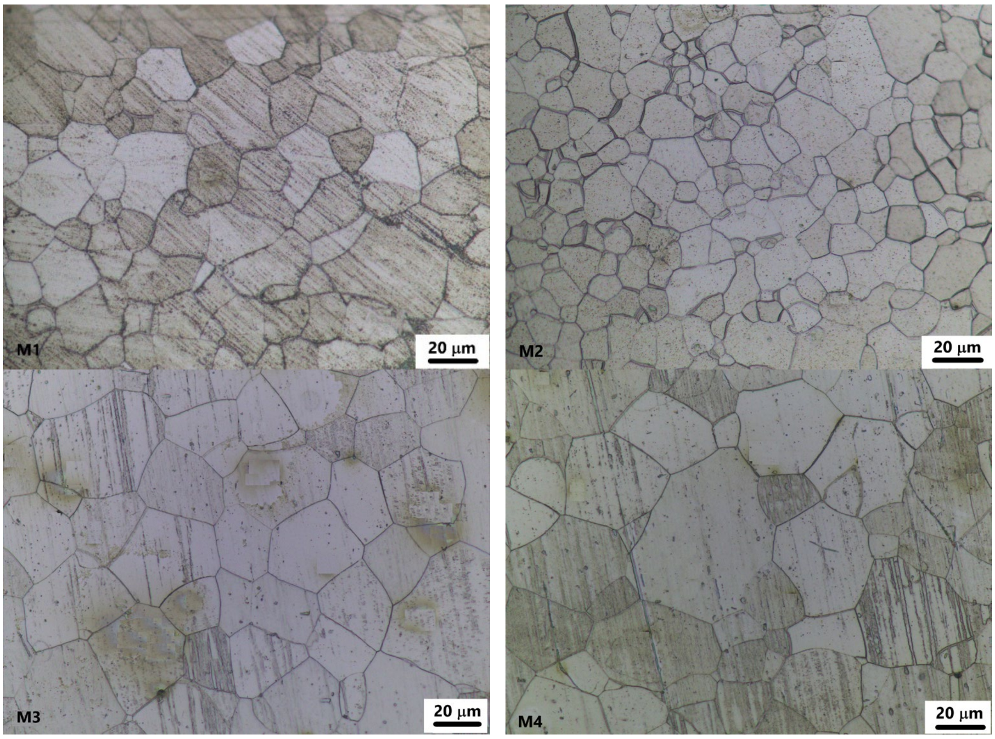

Fig. 1 *Microstructures of the steels (× 500)*

As mentioned above, grain size is an important metallurgical factor that determines the magnetic properties of electrical steel. The grain sizes were estimated and plotted in Figure 2, where the grain size increased with the Si (or equivalent Si) content of steels, even though all the steel samples were annealed under the same conditions. Because grain size reflects the size of magnetic domains, controlling it is a key task in the production of electrical steel. Generally, finer grain size in steel is associated with higher strength; however, this is not suitable for electrical steel due to hindered domain-wall motion and a negative impact on magnetic performance. To optimize magnetic efficiency, it could control grain size through appropriate processing technology by determining the final annealing regimes. The steel M1 Scibisz *et al.* noted that improving the magnetic properties of electrical steel could be achieved by reducing the grain size; however, the grain size should not be too small, as this would increase the number of magnetic domains [11]. Therefore, the grain size of steel M2 was 17 μm, indicating good expectation in mechanical but not in magnetic properties. In contrast, the grain sizes of steel M3 and M4 (30 and 35 μm, respectively) were thought to confer good magnetic properties. In practice, it is speculated that the grain size of the annealed steel exceeds the critical grain size as the annealing temperature is continuously increased, causing eddy-current loss to exceed the reduction in hysteresis loss, and thus the total core loss of the annealed steel increases. This speculation can be confirmed by the results tested by the vibrating sample magnetometer.

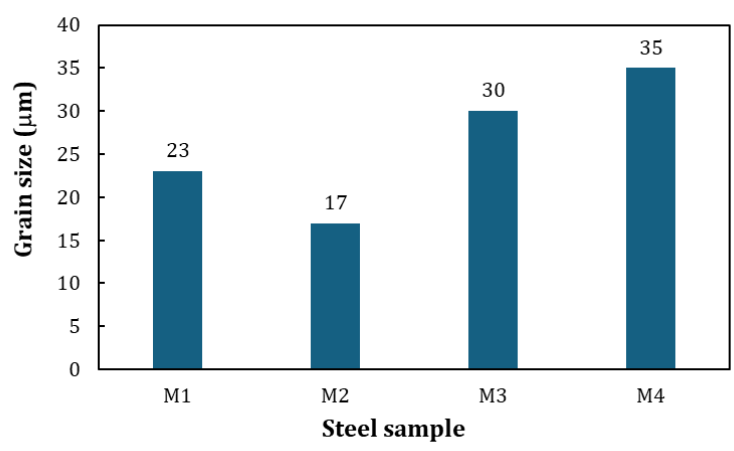

Fig. 2 *Variation of grain size with the steel samples*

Figure 3 shows the magnetized curves for the steels. All hysteresis curves show a steep slope, which is a typical characteristic of soft magnetic materials. Apparently, a basic relation between magnetic properties and metallurgical parameters such as grain size and Si content was seen in all obtained magnetized curves. The fact that the steel could quickly reach the saturated magnetizing state indicated that all steels had high magnetic permeability and low magnetic loss. It is acknowledged that the addition of Si to electrical steel significantly enhances magnetic permeability and electrical resistivity, but it could decrease the coercivity. This was proven by the fact that the saturation magnetization (Ms) of steels M3 and M4 was achieved at a lower magnetic field intensity, compared to steels M1 and M2. The grain size of steel M1 (23 μm) was larger than that of steel M2 (17 μm); however, the magnetic properties were not as good as those of the other steels. This was attributed to the chemical compositions, especially to the Si content. As mentioned above, Si addition rapidly increases the electrical resistivity of iron, resulting in lower eddy current loss and higher efficiency [6,17]. It is acknowledged that larger grains result in smaller coercivity and higher permeability, both of which lead to lower hysteresis. However, larger grains tend to result in greater eddy-current and anomalous losses. According to literature, for low-frequency applications up to a few hundred Hz, large grains were suitable due to decreasing total energy loss, whereas for higher-frequency products, a smaller grain size would be more suitable [1]. It can be admitted that the investigated steels M1 and M2 might be used properly to fabricate the induction cores in electrical motors; meanwhile, the steels M3 and M4 are considered to be suitable for manufacturing transformers.

Table 2 shows a brief comparison of various factors of the studied steel, such as Si-eq, grain size, and magnetic properties. The coercivity of the steel was very low, decreasing from 6.320 (for M1) to 2.425 Oe (for M4). This value was reasonable for soft magnetic materials used in electrical motors, beneficial for demagnetizing and reducing hysteresis loss as the magnetic field was altered during the operation of electrical devices. As steel M1 had the highest coercivity due to the lowest Si content, this steel did not have a clear advantage when used in alternating current. The residual magnetism (Mr) of the steels M1 and M2 was significantly higher than that of other steels (M3 and M4) containing higher equivalent Si content. Generally, a magnet with a higher maximum energy product (BHmax) will be stronger than a magnet with a lower one, but this does not refer to good performance of magnetic field density or flux generation for soft magnetic materials. It meant that the higher BHmax of steel M1 and M2 (94393 and 70121 MGOe, respectively) did not guarantee good performance for typical applications in electrical devices. Steel M4 had the lowest Mr and Hc, indicating that this steel (a soft magnetic material) had prominent properties, e.g., easy magnetic reversibility and low hysteresis loss. The fact that the sample M3 and M4 contained higher Si content was consistent with the finding that saturation magnetization decreases with increasing Si content. It is well established that during magnetization, the rearrangement of the magnetic domain, which is uniformly magnetized or obtains magnetic polarity spontaneously, has a significant effect on the magnetic properties in electrical steels. Grain boundaries and crystallographic orientation in this steel strongly affect magnetic domain behavior. Namely, larger grains in steel M3 and M4 tended to have smaller domain widths, resulting in small Ms; but smaller grain sizes in steel M1 and M2 may lead to higher Ms due to reduced pinning of domain walls. In addition, the lowest saturation magnetization (Ms) of steel M3 was attributed to the homogeneous microstructure, as the same-sized grains promoted magnetic domains to change direction during magnetic testing. During production, residual stress and grain boundaries can pin magnetic domain walls, restrict their movement and reduce permeability, which increases hysteresis loss [18]. Thus, electrical steel with larger grains usually requires a higher Si content. Based on the compositions and resulting magnetic properties, it can be speculated that the steel M1 was a low-C steel only; this steel grade should not be used to produce high-efficiency electric devices.

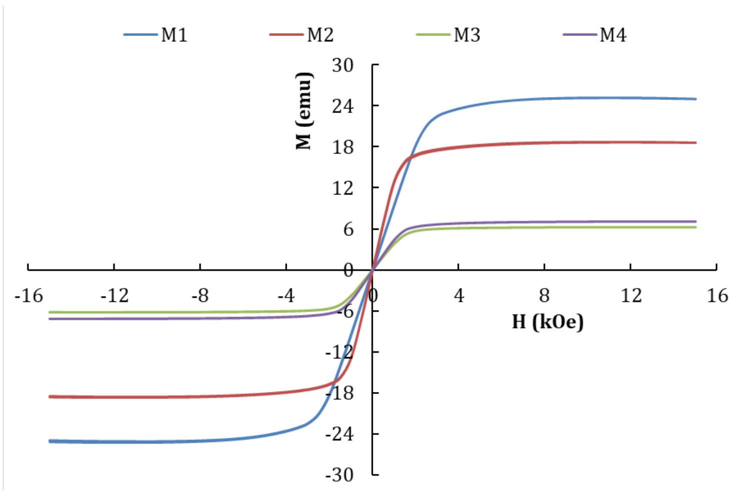

Fig. 3 *Hysteresis curves of the steels*

Table 2 *Summary of various factors for the studied steels*

	Compositions	Microstructure		Magnetic properties		
	Si-eq (wt.%)	Grain size (μm)	Hc (Oe)	Mr (emu)	Ms (emu)	BH max (MGOe)
M1	0.029	23	6.320	0.0602	24.97	94393
M2	0.624	17	3.648	0.0504	18.67	70121
M3	1.135	30	3.153	0.0124	6.21	23586
M4	1.504	35	2.425	0.0114	7.11	26947

4. Conclusion

The present study investigated the changes in microstructure and magnetic properties of several electrical steel grades with Si content, a main alloying element. The chemical composition and grain size were found to influence and correlate with the magnetic properties of the studied steels. The average grain size of the steels varied from 17 to 35 μm, corresponding to the increased Si content in the studied steel. Except for steel M3, the abnormally large grains were observed in almost all steels due to secondary recrystallization during steel production. The steel containing 1.47 wt.% Si showed the best magnetic properties, including a coercivity (Hc) of 2.425 Oe, residual magnetism (Mr) of 0.0114 emu, saturation magnetization (Ms) of 7.11 emu and maximum energy product (BHmax) of 26947 MGOe. It can be concluded that the addition of Si should be carefully decided for a specific device, provided that the efficiency can be obtained. Not only the Si alloying element, but the concept of Si equivalent should be used to adjust the chemical compositions of electrical steel to achieve suitable magnetic properties. Besides compositions, microstructure is an essential factor affecting the magnetic properties of the electrical steel. The higher the Si content is, the larger the grain size needs to obtain a proper magnetic performance. It can be concluded that the magnetic properties of these steel sheets will be useful information for the efficient production and usage of electric steel in practice.

Acknowledgement

The authors would like to express their gratitude to Hanoi University of Science and Technology for providing the necessary administrative support and environment to conduct this research.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Anh-Hoa Bui;* ***data collection:*** *Minh-Hoang Nguyen;* ***analysis and interpretation of results:*** *Anh-Hoa Nguyen, Minh-Hoang Nguyen;* ***draft manuscript preparation:*** *Anh-Hoa Bui. All authors reviewed the results and approved the final version of the manuscript.*

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