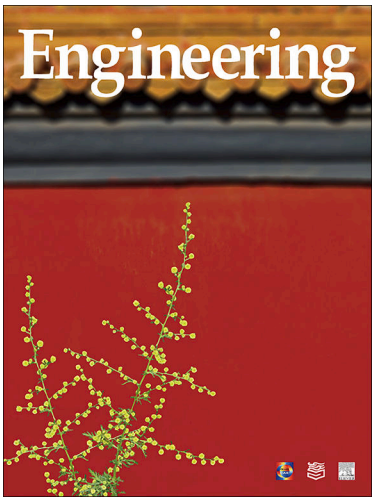
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Views & Comments

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Views & Comments

High-Performance Grain-Oriented Electrical Steel for a Sustainable and Electrified World

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1. Overview

Electric power transmission plays a critical role in the social and economic development of a country. However, the long distances between power plants and electricity consumers result in substantial energy losses, with approximately 8%–15% of electricity lost across transmission and distribution networks worldwide [1]. Transformers are widely utilized in power systems to allow the transmission of electric power at high voltages, which reduces loss due to wire heating [2]. Improving transformer performance has been deemed an essential strategy for increasing the efficiency of energy transmission and reducing greenhouse gas emissions. Grain-oriented electrical steel (GOES) serves as the critical raw material in the magnetic core of a transformer and determines its efficiency and reliability [3]. GOES was invented by Norman P. Goss in 1935, and its main characteristics include a high silicon content and a specific crystalline orientation {110}<001> along the rolling direction (RD), known as a Goss texture [4]. Over time, the chemical composition and microstructure of GOES have been tailored to produce a specific magnetic property—namely, a small hysteresis area, which results in a low power loss per cycle, low iron loss, and high permeability—to improve the engineering performance of GOES and increase its energy transmission efficiency.

With the belief that technological advances in GOES play a critical role in global energy transmission and conservation, we would like to share our views on strategies to realize GOES with a high engineering performance—by pursuing low iron loss, designing eco-friendly coatings, and developing novel GOES manufacturing processes—based on our many years of experience. Fig. 1 provides a pictorial summary of our views.

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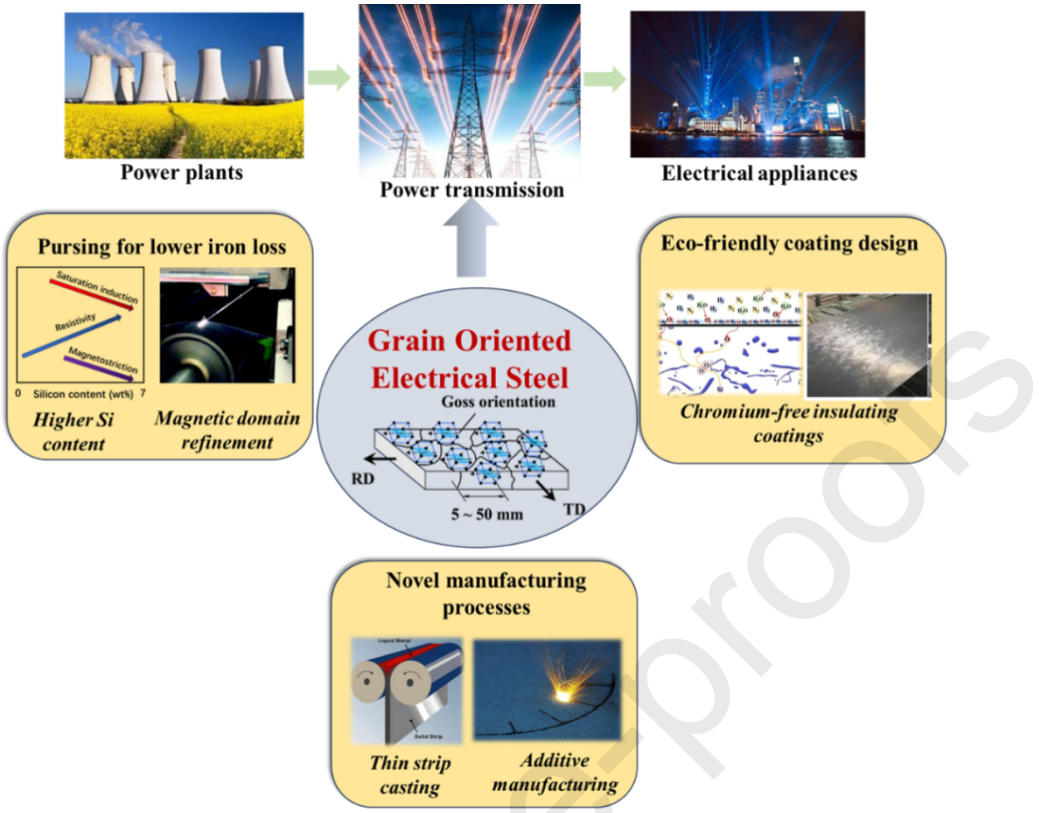


Fig. 1. Schematic illustration of our views on the GOES. RD: rolling direction, TD: transverse direction.

2. Pursuing lower iron loss

When the GOES laminates in transformers are subjected to a changing magnetic field, some of the power that is transferred is inevitability lost or dissipated as heat or noise [5]. Core loss, commonly termed "iron loss," serves as a key indicator of the engineering performance of GOES, and pursuing lower iron loss has always been the utmost priority in GOES research.

From a microstructural perspective, GOES iron loss can be significantly reduced by increasing the silicon (Si) content and improving the {110}<001> Goss texture alignment. From a manufacturing perspective, the production of thinner-gauge material and the development of magnetic-domain-refining techniques have also been demonstrated to be effective approaches for reducing iron loss.

Increasing the silicon content in GOES has proved to be the most direct method for improving the magnetic properties. Recent advances in manufacturing technologies have enabled the development of GOES with a high silicon content of up to 6.5%, where the material exhibits superior engineering performance [6]. However, increasing the silicon content dramatically lowers manufacturability, since the GOES becomes likely to undergo cracking during the rolling process [7]. Extensive research efforts have been made to improve the manufacturability of high-silicon GOES through techniques such as increasing the hot-rolling temperature, incorporating warm rolling into the cold-rolling process, or using direct powder rolling. For example, Ros-Yañez et al. [8] realized a total cracking reduction of 95% by heating the slabs to 1150–1250 °C during hot rolling. Lindemann-Geipel et al. [9] used a powder metallurgy approach to incorporate a high silicon content into GOES that could not be realized using conventional techniques. However, both the high-temperature rolling and the powder metallurgy approaches present challenges associated with geometric and economic boundary limitations. Tailoring the Goss texture through secondary recrystallization is another approach for improving the magnetic properties of GOES. At present, the magnetic induction (B_{800}, measured at 800 A·m^{-1}) of a GOES with a 3.5% Si content, known as Hi-B, can exceed 1.96 T, with a minimum iron loss ($P_{17/50}$, measured at 1.7 T and 50 Hz) reaching 0.61 W·kg^{-1} in the laboratory; this is achieved by sharpening the Goss texture (deviation <2°). However, the reason why the Goss texture develops selectively during the final annealing stage remains unclear, requiring further in-depth investigations. Existing theories and arguments should also be

double-checked to guide the development of annealing technologies and the determination of processing parameters [10]. Also, to achieve the same excellent performance in commercial Hi-B products, future advancements will require the integrated development of compact strip production (CSP), novel composite inhibitors, high-temperature heat-treatment methods, and other processes.

Magnetic-domain refinement is another important approach for improving the magnetic property of GOES. At present, laser scribing is the most commonly used technique due to its non-contact nature and ease of incorporation into existing manufacturing lines [11]. Previous research has shown that, under optimum laser-irradiation conditions, the core loss of GOES can be reduced by about 10% at 1.7 T and 50 Hz [12]. Nevertheless, the fundamental mechanism responsible for magnetic-domain refinement through laser–matter interactions remains unclear because of a lack of direct *in situ* observation. Future research efforts should focus on developing advanced characterization techniques for uncovering this mechanism and thereby proposing more effective laser scribing methods [13]. Another way to reduce the core loss of GOES sheets is to reduce their thickness. However, reducing the sheet thickness introduces several problems that are difficult to avoid, including instability of secondary recrystallization, an increase in hysteresis losses, and an increased possibility of physical damage to the laminates. As a result, a thickness of 0.18 mm is considered optimal for GOES sheets, striking a balance between manufacturing difficulty and customer usability.

3. Eco-friendly coating designs

Insulating coatings play a significant role in the reliability and longevity of transformers by improving the magnetic properties and corrosion resistance of GOES [14]. Eddy current loss can be effectively reduced by the use of an insulating coating to separate the GOES sheets [15]. Moreover, beneficial tensile stress can be introduced to GOES during the baking of the coating at a high temperature, resulting in magnetic-domain refinement and anomalous loss reduction [16]. However, currently used coatings often contain chromium (Cr) and other highly toxic elements, which are environmentally unfriendly. Therefore, developing high-performance, stable, eco-friendly, and Cr-free coatings has become a research focus. However, most Cr-free coatings exhibit an undesirable hot-rolling performance in comparison with their Cr-containing counterparts, due to their low thermal stability [17]. Moreover, Cr-free coatings are more susceptible to corrosion, degrading the engineering performance of transformers.

To develop high-performance and eco-friendly insulating coatings for GOES, future research directions could focus on the development of high-temperature binders, such as $Al(H_2PO_4)_3$, and silica sol coatings that can simultaneously maintain high-temperature resistance and good corrosion resistance [18]. In addition, it has been reported that incorporating finely powdered SiO_2, Al_2O_3, and TiO_2 into a phosphate coating can significantly improve coating integrity and thermal stability [19]. The introduction of nano materials into coatings has also been demonstrated to be an effective approach for improving the magnetic properties of GOES [20]. The influence of component characteristics—including the particle size and composition of additives and fillers—on the overall performance of coatings should be investigated to enable composition and process optimization. In this regard, another important research direction in the field of GOES could involve optimizing coating design in terms of chemistry and process technologies.

4. Novel manufacturing processes

Although GOES manufacturing technologies were first invented over 70 years ago, the further development of GOES manufacturing processes remains an exciting field for industrial and academic research, driven by two main disadvantages during traditional manufacturing processes: ① exaggerated high slab-reheating temperatures and ② very long manufacturing processes. Innovations in future manufacturing processes should be focused on reducing both manufacturing costs and carbon emissions in order to stay competitive on the market. Thin-strip casting and additive manufacturing may be two promising technologies.

(1) **Thin-strip casting.** This technology combines casting and rolling processes by rolling the continuously cast slab directly after maintaining it at a certain temperature in a soaking furnace without cooling. Thin-strip casting can directly produce as-casted strips with a thickness close to that of a conventional hot-rolled strip [21]. This technology offers other benefits in addition to shortening the process: Firstly, continuous slab reheating in a soaking furnace is more homogeneous than the static reheating of a thick slab in a walking beam furnace, leading to a reduced-temperature gradient between the surface and the center of the slab. Therefore, the slab-reheating temperature can be much lower than 1400 °C that is typically used in the conventional manufacturing process and can jeopardize the formation of inhibitors. Moreover, reducing the temperature permits higher dimension preciseness by reducing fluctuations in slab geometries. In addition, greater inherent

inhibition can be obtained during the strip-casting process, resulting in GOES with a broader range of primary grain sizes, which can be adjusted during post-processing [22].

(2) **Additive manufacturing.** Additive manufacturing technology is regarded as a remarkable paradigm for the production of high-performance components for energy, automotive, aerospace, and medical applications [23]. Traditional metal additive manufacturing processes can be categorized into four groups: powder bed fusion, binder jetting, direct energy deposition, and sheet lamination [24]. These techniques allow the fabrication of parts with complex and customized geometries and can be applied to GOES manufacturing. One particular advantage of additive manufacturing for GOES is its capability to produce high-silicon (up to 6.5%) GOES with higher electrical resistivity, near-zero magnetostriction, and lower magnetocrystalline anisotropy than traditional GOES [25]. Moreover, the print-on-demand nature of additive manufacturing can offer high flexibility for tailoring the crystallographic texture of GOES with novel microstructures [26]. Despite the capabilities and versatility of additive manufacturing methods, utilizing additive manufacturing to produce GOES on a large scale still presents many manufacturing, research, and economic challenges. For example, the size of additively manufactured GOES sheets is often limited to a scale of about 10 cm, which cannot meet critical demands for transformer applications. Moreover, printing strategies and parameter optimization must be further explored to eliminate structure porosity, reduce microstructure heterogeneity, and improve the overall magnetic properties [27]. Furthermore, additive manufacturing remains a costly option for producing GOES, largely due to expensive raw materials, high machine costs, and low building speed.

5. Conclusions

As a soft magnetic material, GOES serves as the core material in electric transformers. Despite nearly 70 years of technological development, extensive research efforts are needed in GOES design, fabrication, and processing to achieve superior energy efficiency and environmental performance. This paper proposed our views on future research directions for GOES in terms of pursuing lower iron loss, designing eco-friendly coatings, and developing novel manufacturing processes. Scientific and technological gaps associated with these directions were also discussed. With advancements in gaining a deep scientific understanding of the material and novel technological innovations, GOES could play an increasingly prominent role in conserving energy and reducing greenhouse gas emissions throughout society.

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References

[1] Doukas H, Karakosta C, Flamos A, Psarras J. Electric power transmission: an overview of associated burdens. Int J Energy Res 2011;35(11):979–88.

[2] Li Y, Yi BW, Wang Y. Can ultra-high voltage power transmission bring environmental and health benefits? An assessment in China. J Clean Prod 2020;276:124296.

[3] Deželak K, Petrun M, Rošer M, Dolinar D, Štumberger G. The impact of iron core model on dynamic behavior of three-phase power transformer dynamic model. IEEE Trans Magn 2015;51(1):8400104.

[4] Goss NP. New development in electrical strip steels characterized by fine grain structure approaching the properties of a single crystal. Trans Am Soc Met 1935;23(1):511–31.

[5] Hamzehbahmani H. Static hysteresis modeling for grain-oriented electrical steels based on the phenomenological concepts of energy loss mechanism. J Appl Phys 2021;130(5):055102.

[6] Pan H, Zhang Z, Xie J. The effects of recrystallization texture and grain size on magnetic properties of 6.5 wt% Si electrical steel. J Magn Magn Mater 2016;401:625–32.

[7] Zhang B, Ye F, Liang YF, Shi XJ, Lin JP. The rolling performance of Fe–6.5 wt.% Si sheets edged with stainless steel. Mater Res Express 2017;4(10):106507.

[8] Ros-Yañez T, Houbaert Y, Fischer O, Schneider J. Production of high silicon steel for electrical applications by thermomechanical processing. J Mater Process Technol 2003;143–144:916–21.

[9] Lindemann-Geipel I, Mix T, Thamm M, Höhnel C, Weise B, Reuter K, et al. Potential of powder metallurgical methods to fabricate Fe–6.5Si soft magnetic components. Powder Metall 2024;67(2–3):129–37.

[10] Yilmaz C, Poul M, Lahn L, Raabe D, Zaefferer S. Dislocation-assisted particle dissolution: a new hypothesis for abnormal growth of Goss grains in grain-oriented electrical steels. Acta Mater 2023;258:119170.

[11] Ito N, Itagaki H, Ohta M. Core loss reduction through a laser scribe on Fe-based amorphous ribbon surface for transformer cores. J Magn Magn Mater 2022;564(Pt 2):170168.

[12] Xia Z, Kang Y, Wang Q. Developments in the production of grain-oriented electrical steel. J Magn Magn Mater 2008;320(23):3229–33.

[13] Jahangiri MR, Bayani H, Ardestani M, Mehdizadeh M. Core loss reduction in grain oriented silicon steel sheets by two-sided laser scribing in the presence of a magnetic field. J Alloys Compd 2022;891:162080.

[14] Tamma WR, Prasojo RA, Suwarno. High voltage power transformer condition assessment considering the health index value and its decreasing rate. High Volt 2021;6(2):314–27.

[15] Hu X, Zhang X, Liu J, Wu K, Lin A. Development and performance of phosphate-based protective insulation coating for non-oriented electrical steel. J Chin Soc Corros Prot 2022;42(5):805–12. Chinese.

[16] Beyer E, Lahn L, Schepers C, Stucky T. The influence of compressive stress applied by hard coatings on the power loss of grain oriented electrical steel sheet. J Magn Magn Mater 2011;323(15):1985–91.

[17] Liu T, Luo ZH, Mao JH, Yang H, Hu ST. The effects of chromium-free insulating coating on the magnetic properties in grain-oriented electrical steel. Adv Mater Res 2013;813:100–3.

[18] Zhang Y, Liu P, Ding Z. Anticorrosion property of chemically bonded phosphate ceramic coatings with silica sol. IOP Conf Ser Earth Environ Sci 2020;571:012099.

[19] Liu Y, Wu L, Chen A, Xu C, Yang X, Zhou Y, et al. Component design of environmentally friendly high-temperature resistance coating for oriented silicon steel and effects on anti-corrosion property. Coatings 2022;12(7):959.

[20] Goel V, Anderson P, Hall J, Robinson F, Bohm S. Electroless Co–P–carbon nanotube composite coating to enhance magnetic properties of grain-oriented electrical steel. J Magn Magn Mater 2016;407:42–5.

[21] Liu HT, Yao SJ, Sun Y, Gao F, Song HY, Liu GH, et al. Evolution of microstructure, texture and inhibitor along the processing route for grain-oriented electrical steels using strip casting. Mater Charact 2015;106:273–82.

[22] Song HY, Liu HT, Lu HH, An LZ, Zhang BG, Liu WQ, et al. Fabrication of grain-oriented silicon steel by a novel way: strip casting process. Mater Lett 2014;137:475–8.

[23] Wang Y, Mao B, Chu S, Chen S, Xing H, Zhao H, et al. Advanced manufacturing of high-speed steels: a critical review of the process design, microstructural evolution, and engineering performance. J Mater Res Technol 2023;24:8198–240.

[24] Bajaj P, Hariharan A, Kini A, Kürnsteiner P, Raabe D, Jägle EA. Steels in additive manufacturing: a review of their microstructure and properties. Mater Sci Eng A 2020;772:138633.

[25] Macknojia AZ, Tran JV, McKinstry MP, Galindo J, Jin Y, Dowden S, et al. Additive manufacturing of Fe–6.5 wt.%Si transformer steel toroidal cores: process optimization, design aspects, and performance. Mater Des 2024;241:112883.

[26] Niendorf T, Leuders S, Riemer A, Richard HA, Tröster T, Schwarze D. Highly anisotropic steel processed by selective laser melting. Metall Mater Trans B 2013;44(4):794–6.

[27] Teh WH, Tan LP, Chen S, Wei F, Lee JJ, Padhy SP, et al. Breaking conventional limits of silicon content in Fe–*x*Si magnetic alloys through additive manufacturing. J Alloys Compd 2024;983:173829.

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