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RESEARCH ARTICLE

Review of Electrical Steels with their Properties and Recent Trends for Improvement

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Abstract

Objectives: This review study provides a thorough analysis of the magnetic behavior and characteristics of electrical steels, including established and novel materials (3%wt Silicon). **Methods:** We investigate how composition, microstructure, and processing methods affect the magnetic performance of these steels as well as the basic principles guiding their behavior. Thermomechanical processing can be observed for its impact on the material's microstructure and magnetic properties. This review discusses testing over samples for conventional processes for different % of cold worked or strain hardening and annealing at higher temperatures i.e., 1200°C. For uncertainties regarding the impact of impurities or inclusions on their magnetic properties, the study was carried out to know the effect of cerium addition on the material's magnetic properties of the material. **Findings:** It was observed that rolling temperature has significant effect over magnetic properties of the material. A notable improvement in the magnetic permeability of the material and its critical performance metric for soft magnetic materials is indicated by the increase in "Gamma max". Similarly, the effects of compressive stresses, doping effect, grain size, annealing, and other manufacturing processes were studied, and observed their impact on magnetic properties. This review discusses the literature on future scope with the latest trends. This helps clarify the trade-offs associated with maximizing electrical steels for certain uses. **Novelty:** This study presents a novel approach towards electrical steel and its magnetic properties by incorporating different alloying elements and optimizing rolling & annealing parameters. A key innovation is the application of machine learning and neural network to predict and optimize material behavior, core loss and provide methods to improve magnetic properties of electrical steels. **Significance:** Electrical steels are crucial in transformers and electric motors, enhancing efficiency by minimizing energy losses and improving magnetic performance. This can be achieved by changing manufacturing parameters and operating conditions with the help of latest trends.

Keywords: Electrical steel; Magnetic properties; Machine learning; Composition; Microstructure; Core loss

1 Introduction

Electrical steel sheets that are not orientated (NO) are used in rotating machinery such as wind turbine generators, transportation sector motors, and tiny kitchen appliance motors. These devices are becoming more and more significant because to the present trend of switching from fossil fuel-based energy conversion to electricity-based energy conversion. As a result, they have a significant leveraging effect on energy savings through increased efficiency. It is generally known that various electrical machine applications have distinct needs when it comes to the characteristics of NO electrical steel sheets, which are derived from their microstructures and textures. The intricate interaction between processing processes, many phenomena occurring, and the final material qualities remain inadequately understood, making the design and production of customized NO electrical steel sheets difficult[1].

A lot of research has been carried out in the field of electrical steel to improve its properties. However, the effects of different processes on the magnetic behavior of silicon steel are not yet fully explored. This review has been focused on latest trends and innovations done in recent years which will create more scope for research activities in this field. There are fields like Additive manufacturing that can be used to explore more exploring magnetic properties of electrical steels. This review paper will describe recent research contributions on electrical steels in reducing power losses and improving permeability. Also, we will discuss research gaps that can be helpful in improving the magnetic characteristics of electrical steels. We have certain limitations as well to explore the magnetic behavior of the steels, particularly for electrical machines used in high-speed applications. However, in today's world using advanced machine algorithms we can predict electrical steel behavior under high-speed applications.

The necessity for effective and sustainable electromobility has grown recently. Additionally, there has been a growing interest in highly adaptable resource-saving production methods. Scalable production solutions are taking the place of standardized manufacturing of electric powertrains in order to achieve this goal. That being said, the future generation of electrical machinery can be produced using additive manufacturing (AM) technology due to its unparalleled versatility. The fact that the stator and rotor of the current electrical machines are only made with 2D electrical steel laminations, leaving no room for design freedom in the third dimension, is one of their primary problems. The goal of the literature review is to 3D print premium magnetic materials. Unconventional solutions can be industrialized thanks to various AM methods, and magnetic material powders with varying chemical compositions can be tailored for a variety of applications[2].

1.1 Research Contributions

Research contributions in electrical steels and their magnetic properties have been substantial, reflecting the material's critical role in modern electrical machinery such as transformers, motors, and generators. These contributions show various aspects, from material development to advanced characterization techniques. Here's an overview of key research contributions:

1.1.1 Development of High-Silicon Electrical Steels

Silicon Alloying: The inclusion of silicon in steel has been a major development, as it helps reduce core losses and increase electrical resistivity. Research has optimized the silicon content (typically up to 6.5%) to balance magnetic performance with mechanical properties. Larger grain sizes led to in-grain shear bands developing and coarser deformed grains, both of which exhibited unique recrystallization behavior. Strong γ-fiber recrystallization texture was produced at a later stage of the process due to quick kinetics caused by the formation of new normal direction grains, which was previously caused by a small-grained microstructure. However, because of the diverse nucleation orientation and the quick grain development in the interior of coarsely deformed γ-grains with the aid of in-grain shear bands, the previous big-grained microstructure led to comparatively fast recrystallization kinetics at an early stage[3].

However, a high silicon addition may cause the steel to become hard and brittle, which results in poor cold workability. A coarse grain can reduce hysteresis loss and hence grain size is always a key component in governing core loss. Increasing the λ-fiber texture in the electrical sheet plane with two easily magnetized $< 001 >$ orientations can increase the magnetic induction. Therefore, optimizing grain size and concurrently enhancing the recrystallization texture is a useful strategy to achieve both high magnetic induction and minimal core loss[3].

The impact of Fe nanoparticles on the microstructure and soft magnetic characteristics was examined, with a mass fraction ranging from 0 to 7 weight percent. Fe nanoparticles may efficiently fill the holes between Fe-6.5 wt% Si powders, increasing the density of the SMCs in line with this. Simultaneously, compared to the absence of Fe nanoparticles, the magnetic permeability of the SMCs mixed with varying mass fractions of Fe nanoparticles has greatly enhanced and shows good frequency stability. It also shows that by lowering the intra-particle eddy current loss, the addition of 1 weight percent Fe nanoparticles can lessen the eddy current loss of the SMCs. The SMCs show good magnetic characteristics with strong magnetic permeability and comparatively minimal core loss when Fe nanoparticles are added at a weight percentage of 3 wt% [4].

Improved Ductility: Researchers have also focused on overcoming the brittleness associated with high-silicon steels by developing new processing techniques, for example, rapid solidification and hot rolling, to maintain good ductility. By streamlining their production process, electric machines can operate more energy efficiently. Significant tensions are introduced around cutting edges during the production process. Without an external mechanical load, the steel is in a plastically deformed stress state close to the cutting edges. A customized magneto-mechanical measuring setup, stress-strain measurements, electrical resistance measurements, and transmission electron microscopy (TEM) measurements are used to examine the magnetic characteristics of the steel in this stress state. The loss separation approach is used to analyze the core energy losses. Sample deformation was examined for its impact on the magnetization curve and total core energy losses, both prior to and following the release of the mechanical load. It is well known that under mechanical load, the magnetic characteristics drastically deteriorate as sample deformation increases [5].

1.1.2 Review of Texture Evolution

The development of new goods is a complicated endeavor because the evolution of texture and magnetic behavior of non-grain-oriented electrical steels depends on various aspects, including heat treatment, chemical composition, and rolling method. The study's findings suggest that more investigation is needed to guarantee higher permeability and lower core loss characteristics for non-grain-oriented silicon steels. To benefit the steelmaking community, an assessment of different factors and their impact on the evolution of texture of non-grain-oriented electrical steels would be beneficial. Engineers can better regulate the texture and magnetic characteristics of NGO electrical steel by understanding these interactions [6].

Because phosphate offers high electrical insulation and corrosion resistance, it has been employed as a coating agent in several sectors, including electrical steel. Even if a phosphate coating's insulating qualities can greatly reduce the iron loss of the sheet, a new coating substance should be created to increase the sheet's performance even more. In this study, we created hybrid coating agents that combine organic and inorganic elements to provide better insulation than traditional phosphate coating agents. Starting materials included silane coupling agents and inorganic particles (SiO_2, TiO_2, and Cr_2O_3) with good insulating qualities. Good dispersion stability of the coating agent was achieved by silane coupling agents with the right solvent content, which effectively modified the surfaces of inorganic particles. The good surface roughness of the hybrid materials coated on the ES was ascribed to the homogeneous dispersion of the coating agent. Ultimately, after applying the hybrid coating agent with the ideal composition on the ES, the hybrid coating's insulating property outperformed the traditional phosphate coating's corrosion resistance. [7]

1.1.3 Advanced Manufacturing Techniques

Electrical steel is considered a soft magnetic substance used in generators, transformers, and motors and can be made in a number of ways. A great deal of study has been done on how thermomechanical production techniques like hot rolling, cold rolling, and multistage annealing can improve the metallurgical properties of electrical steel.

The improvement of silicon steel's mechanical and magnetic properties is significantly influenced by these manufacturing processes. Alloying elements are usually added at the casting step in conventional ways of manufacturing electrical steel in order for them to precipitate as regular grain growth inhibitors, which ultimately affect the magnetic characteristics of the finished product. The materials like aluminum nitride (AIN) and Manganese sulfide (MnS) disintegrate at temperatures as high as 1400 °C during the reheating step. The processes like Pre-rolling can result in portions of the slab's surface areas remelting during the high-temperature slab, which can pose issues with rolling and annealing.

Using an electron backscattered diffraction (EBSD) scanner and a scanning electron microscope, the effects of hot band annealing on the inclusions, texture, and magnetic properties of a 0.3 mm thick sheet of 2.97% silicon - 0.59% aluminum non-oriented silicon steel were examined. The inclusions in the hot band clearly decreased as the hot band annealing temperature rose, and during the hot band's recrystallization, the area fraction texture noticeably increased. The ultimate sheets' texture was primarily composed of γ^*- and γ-fiber textures. Additionally, raising the hot band annealing temperature led to an increase in grain size, strengthening the θ-fiber texture and weakening the γ-fiber texture of the finished sheets, which improved iron loss and magnetic induction [8].

1.1.4 Energy-Efficient Electrical Machines

Silicon steel is the preferred material for the core of machines like transformers due to its magnetic behavior. It has higher magnetic permeability and lower hysteresis loss, which means it can efficiently transform electrical energy from one voltage level to another with minimal energy losses. The Chinese Standardization Administration released the mandatory standard which states "Minimum allowable value of energy efficiency and the energy efficiency grades for power transformers" (GB20052-2020) in an effort to lower transformer losses.[9]. While some of the standards are a little stricter than the EU standard, overall, this new standard is in line with the most recent EU standard. The new power transformer standard's Level 1 and Level 2 grades have no-load losses that are 35% and 45% lower, respectively than the previous standard. China released the "Transformer Energy Efficiency Improvement Plan (2021–2023)"[9] in December 2020, which stipulated that by 2023, more than 75% of higher efficiency and best transformers in energy saving parameters that complied with the new two levels i.e., 1 and 2 requirements must be in place. The application of these new guidelines[9].

The high temperatures are required for additive manufacturing processes like laser sintering and metal 3D printing where the fusion of material takes place. Printing plastic parts often uses less energy than older methods. By combining manufacturing processes, enabling localized output, and utilizing less energy for transportation, additive manufacturing can lower overall energy consumption. Unlike subtractive techniques such as milling, drilling, etc additive manufacturing reduces waste by using only the material required for each item, as parts are constructed layer by layer. Certain additive manufacturing materials are challenging to recycle, and support structures that are required for some designs. It may increase waste. Although processes like additive manufacturing generally use less energy, it can be energy-intensive, particularly when working with metals. The current industrial landscape clearly demonstrates the sustainability benefits of additive manufacturing and technical domination, which are being established with key industries. Finding out which additive manufacturing technologies are more environmentally friendly than traditional production is the key objective. Now, industries can choose the right technologies to achieve environmental targets[10].

1.2 Research Gaps

Though the problem is not new and many research activities have been done in a similar field, still there are research gaps in the field of electrical steel. Its magnetic properties are of significant interest, particularly as the demand for more efficient electrical machines and devices grows. Electrical steel is a key material used in transformers, motors, and generators, and its magnetic properties are crucial for energy efficiency. Here are some notable research gaps:

1. The effect of non-metallic inclusions like SiO_2 in ferromagnetic materials is not fully understood, so the Impact of inclusions and impurities on Magnetic Properties. These factors can significantly influence core losses, but their effects are not yet fully quantified. Specific alloys which contain REM oxides like Cr-C-N, Cr-Mn-O, and Al_2O_3 have not been studied fully so their influence on steel quality is unknown.
2. Advanced Coating Techniques: Insulating coatings are critical in reducing eddy current losses in electrical steel. Research is needed to develop coatings that can withstand high temperatures and stresses while maintaining low-loss characteristics. Developing coatings that are both effective and environmentally friendly is a key challenge. The trade-off between coating performance and environmental sustainability is an area that requires further investigation.
3. Modelling and Simulation of Magnetic Behavior: there is a gap in multi-scale modeling that accurately predicts the magnetic behavior of electrical steel from the atomic level to the macroscopic level. This includes understanding the effects of grain boundaries and phase distribution. The impact of magnetostriction on the performance of electrical machines is an area that lacks comprehensive models. Accurate simulation tools that can predict these effects under different operating conditions are needed.
4. Impact of Manufacturing Processes: The effects of the rolling process and annealing at higher temperatures on the microstructure and, consequently, the magnetic properties are well known, but the underlying mechanisms need further exploration. The relationship between process parameters and final magnetic properties is still not fully understood. The potential of additive manufacturing (AM) for electrical steel components is an emerging area.
5. Magnetic Aging: The long-term stability of magnetic properties under operational conditions, such as stress, temperature, and magnetic field cycling, is not fully understood. Research is needed to predict the aging behavior and its impact on performance.
6. Impact of Magnetization Dynamics: There is a need for a better understanding of domain wall dynamics during magnetization processes, particularly under high-speed and high-frequency conditions. The mechanisms behind magnetic hysteresis in different grades of electrical steel and under varying conditions (stress, temperature, etc.) require further study to optimize material performance.

These gaps indicate areas where focused research could lead to significant advancements in the performance and sustainability of electrical steels, which are critical for energy-efficient technologies.

1.3 Research Questions

1. What are the specific types of non-metallic inclusions and impurities commonly found in ferromagnetic materials, and how do their concentrations correlate with changes in magnetic properties such as permeability, coercivity, and core losses?
2. How do different coating materials and application techniques influence the thermal stability, mechanical durability, and electrical insulation properties of coatings under operating conditions typical of electrical steel applications?
3. What are the key factors at the atomic and microscopic levels, such as grain boundaries and phase distributions, that influence the macroscopic magnetic behavior of silicon steel, and how can these be integrated into a comprehensive multi-scale modeling framework?
4. What are the underlying mechanisms at the atomic and microscopic levels that govern the relationship between rolling/annealing processes and the resulting magnetic behavior of silicon steel?
5. How does magnetic aging affect the long-term stability of magnetic properties in materials under operational conditions, including stress, temperature, and magnetic field cycling, and what mechanisms govern this behavior?
6. What are the specific mechanisms governing domain wall motion in electrical steel during high-speed and high-frequency magnetization, and how do these mechanisms differ across various grades of the material?

2 Review Methodology

2.1 Non-metallic inclusions and impurities in ferromagnetic materials

the direct and substantial impact that ferroalloy impurities have on the quality of steel products. Understanding the primary trace elements and inclusions like ferro silicon, ferro manganese, silico manganese, etc, and some complicated ferroalloys and how these ferroalloys behave in steel melt after addition requires extensive research[(11)].

In one of the researches, study was carried out to know the effect of the addition of cerium on material cleanliness and so on the magnetic behavior of electrical steel[(12)]. There is a mechanism when the material gets magnetized called a microscopic mechanism where magnetic domains disorderly align themselves with an external field with the help of the motion of domain walls of the magnetic field. This process is generally influenced by defects found in the material microstructure such as grain boundaries, dislocations, and non-metallic inclusions, as well as the cleanliness of the material. The motion of the walls of the domain also impacts the magnetic properties of the materials, including magnetic susceptibility and coercivity. The author manufactured four cast ingots of electrical steel with a composition of varying Ce by using the process of vacuum induction melting (VIM) at a higher temperature of 1550°C, with pure metals only. The Iron-Nickel alloy composition is shown in Table 1.

Table 1. Iron-Nickel Alloy Composition [(12)]

Sr. No	Ni	Fe	Mo	Mn	Si	Al	Ce
0#	79.13	14.89	5.21	0.56	0.25	0.015	0
1#	79.08	14.83	5.17	0.56	0.25	0.015	0.007
2#	79.03	14.82	5.18	0.56	0.25	0.015	0.013
3#	79.11	14.79	5.17	0.55	0.25	0.015	0.025

The equipment Leco TC 500 N/O analyzer, ARL4460 direct reading spectrometer, and ICAP 6300 ICPOES analyzer was used to measure the chemical compositions. The inclusions were observed using a Zeiss EVO18 scanning electron microscope equipped with an energy dispersive spectrometer (EDS), and the statistics of inclusions were examined using the Aztec-steel automatic inclusion statistics tool. The application had a view field area of 4 mm^2. The samples were cold rolled to a thickness of 1 mm after being cut into a piece with a thickness of 15 mm.

After that, the samples were water quenched to maintain their annealed state after being annealed under vacuum for 240 minutes at 1200 °C. The Lakeshore7407 vibrating samples magnetometer was used to measure the samples' magnetic characteristics, which were found improved. But still, there is a very vast scope to get the effects of impurities and inclusions over magnetic behavior.

2.2 Influence of compressive stress over magnetic behavior

There is disagreement on the quantitative stress-loss relationship, despite the fact that numerous articles have documented the detrimental impact of compressive stress on power loss. This dispersion of results could be caused by a few factors, including local grain orientation (beneath the pickup coil), average grain orientation, and stress from the coating layer. Two of these variables have been discussed in the research. Three sheet samples were taken of GOES, grade H110-0.27, and they were tested under compressive stress in order to provide repeatable results. These samples will now be considered as A, B, and C. The samples are parallel to the direction of rolling and have a Goss texture with a thickness of 0.27 mm. The samples were submerged for four minutes in hot solutions of NaOH and HCl (around 80°C) to remove the isolating coating. Using an Omega instant adhesive (model SG 496), a strain gauge was bonded posteriorly in the rolling direction. The strain gauge was having a gauge factor of 2.14 and 350 Ω.[13]

With the use of a pick-up coil, a Soken tester called Single Sheet Tester (SST), was applied to the magnetic field (H) and noted the magnetic induction (B). The model used is DAC-BHW-5. Concurrently, the model NI 9237 Wheatstone Bridge from National Instruments was used to measure the longitudinal magnetostriction (λ) in conjunction with a strain gauge. A custom software was developed utilizing the Labview programming language to obtain real-time data on the magnetostrictive experimental data (λ) and hysteresis loops (H and B) using NI USB-6259 and NI 9237, respectively. With a peak value of magnetic induction of 0.7 Tesla, 1.0 Tesla, 1.3 Tesla, 1.5 Tesla, and 1.7 Tesla, all experiments were run at 60 Hz. Additionally, this software measured the peak-to-peak magnetostriction, calculated the power loss (hysteresis loop area), and plotted the hysteresis loops (H vs. B). As shown in Figure 1, a fabricated aluminum frame measuring 334.2 × 200 × 50.8 mm was constructed and fastened at SST in order to exert compressive stress. In addition, the use of two anti-buckling guides kept the sample rigid when the mechanical load was applied.

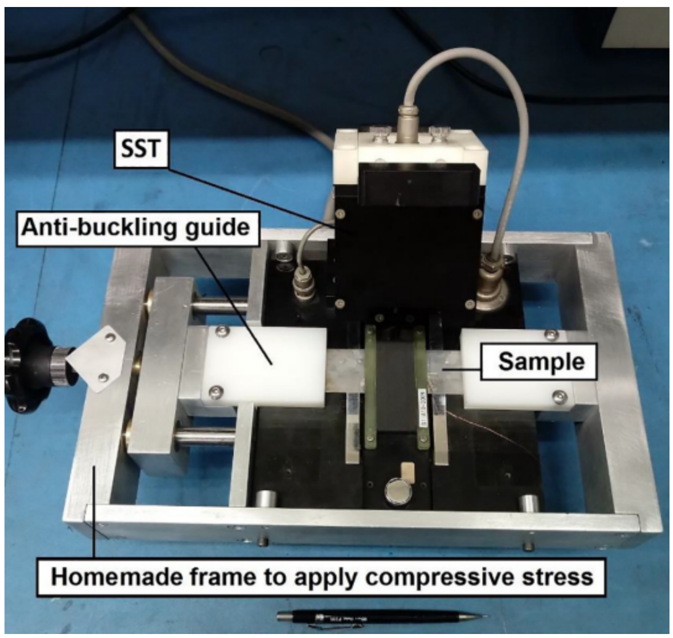

Fig 1. Photograph of the single sheet tester frame [13]

2.3 Analyzing the atomic and microscopic levels, such as grain boundaries and phase distributions

Initially, a vacuum induction furnace was used to melt metallic silicon with industrial pure iron to create the silicon steel ingot (3.5 wt%). Table 2 displays the ingot's chemical makeup. To create HRSs, the ingot was hot rolled to 1.5 mm at 1050 °C after being forged to a thickness of 20 mm between 1050 and 1100 °C.[14]

After the pickling process two more routes were planned, they are:

Route I: an 82% reduction in cold rolling the HRSs to 0.27 mm was achieved after several passes at room temperature. The last annealing was done in a tube furnace with an Ar environment for ten minutes at 800, 900, and 1000 degrees Celsius.Route II: For 20 minutes, the hot rolled steels were normalized at a higher temperature of 1273 K (1000 °C). The cold rolling and annealing procedures were then completed in the same manner as described in Route I. Figure 1 displays the rolling process schematic diagram.

Table 2. The chemical composition of steel ingots [14]

Element	Si	C	Mn	P	N	S
Composition	3.52	0.008	0.017	0.0066	0.0028	0.0029

An optical microscope was used for the observations and analyses of the metallographic microstructure. Using a diffractometer (XRD called X-ray diffractometer), the macrotexture of the material was assessed. The material was original cold-rolled sheets. Using a series expansion method, the orientation distribution function (ODF) was quantitatively computed based on incomplete pole figures {110}, {200}, and {211}.

A scanning electron microscope is a type of electron microscope that was designed specifically to study solid surfaces. The model of microscope used was Zeiss Gemini450 and it was fitted with an Electron Back Scattering Diffraction detector (EBSD), which was used to find orientation image maps. On the MATS-3000Mk50, the magnetic characteristics of 0.27 mm thick silicon sheets passed through the annealing process were assessed by the single sheet method. The samples chosen were taken to the dimensions of length in 300 mm in the direction of rolling (RD) and 30 mm in the transverse direction (TD). Three parameters were measured: iron loss P15/50 (1.5 Tesla and frequency of 50 Hz), magnetic induction B50 (about 5000A/m), and P10/400 (at 1.0 Tesla and 400 Hz). [14]

The balance between strength and magnetic characteristics is complicated in the creation of higher-strength NGO silicon steels for new energy vehicle drive motors. More precisely, a 96% thickness decrease during the hot rolling process aided in the microstructure's homogenization during the normalization treatment that followed. The iron loss was then suppressed to a lower value of 15.6 W/kg thanks to a deformation degree of 80 percent during cold rolling, which also guaranteed the inheritance of the uniform microstructure and prevented the aberrant growth of recrystallized grains after annealing. Meanwhile, the annealed sheet's texture and λ-fiber inheritance were encouraged by this combined process, raising the magnetic induction intensity B50 to 1.606 T [15].

The author has developed a multi-scale model to control the microstructure and texture of a Copper alloyed strength non-oriented electrical steel by varying the thickness reduction of hot and cold rolling processes in an effort to achieve exceptional magnetic characteristics. However, there are certain challenges in the real-time optimization of electrical steel production. It is extremely difficult to accurately link and simulate in a single, real-time model phenomenon such as atomic-level interactions, intermediate grain orientation, texture development, and macroscopic properties across multiple scales. It is challenging to capture the fine-grained impacts of atomic interactions and relate them in real-time to macroscopic consequences like mechanical durability and core losses. It's possible that many steel producers lack the staff and expertise required to put these systems in place and keep them running. Furthermore, retraining a large portion of the staff and reorganizing procedures may be necessary to incorporate new modeling tools into the current manufacturing lines [15].

Simplified models, on the other hand, might provide a compromise between computing efficiency and accuracy by concentrating on the most important characteristics that impact the macroscopic properties, which makes real-time implementation more possible. By providing real-time predictions based on patterns in sensor data and historical results, AI-driven optimization can enhance multi-scale modeling and enable more useful implementation of multi-scale models in real-time scenarios.

2.4 Rolling/annealing processes and the magnetic behavior of electrical steel

The annealing process has an impact on the diffusion of silicon pairs which are generally short range. A crystal lattice elastic strain results from the application of a magnetic field or mechanical stress, and if the temperature range is high enough so that can promote atomic diffusion, the silicon pairs may reorganize themselves to relieve the stress related to this crystal lattice. They may also change their direction to align with the AS's mechanical stress/magnetic field direction. These new silicon pair locations will be maintained after the sample cools to room temperature, resulting in the introduction of an extrinsic magnetic anisotropy that lowers the power loss, or the area of the hysteresis loops. [16]

Two commercial grades of grain-oriented electrical steels (GOES) with varying Goss texture intensities were used for the AS. It is anticipated that the AS will improve the performance of the power transformer by lowering the GOES energy loss. In order to assess the extrinsic magnetic anisotropy, the four magnetic inductions (0.7 Tesla, 1.0 Tesla, 1.3 Tesla, and 1.5 Tesla) were examined for power loss both before and after the AS. Additionally, permeability, remanence, and the coercive field were assessed. Commercial-oriented electrical steel grades R130-27 and H110-0.27 are employed; going forward, they will be referred for testing as two different grades i.e. A and B, respectively. Furthermore, for grades A and B, an indirect measure of intensity of Goss texture B8 is 1.78 Tesla and 1.88 Tesla, respectively. To fix the samples to a load frame EMIC (DL 1000 model), two holes were created of 10 mm diameter each at the ends of each commercial Grain oriented electrical steel grades A & B after the samples were cut to the dimensions of $210\times30\times0.27$ mm. The remaining tension caused by these procedures was eliminated by heat-treating the material for one hour at 840°C in an argon environment.

The Grain Oriented (GO) coatings can be removed by using heating solutions like sodium hydroxide NaOH and hydrochloric acid HCl (80°C) in order to prevent uncontrollably high external influences on stress levels. Samples in this state will henceforth be referred to as received (AR). With regard to the magnetic measurements, a Soken tester called a single sheet tester (SST), a model specified as DAC-BHW-5, was used to magnetize the samples in a rolling direction. Using a primary coil, the SST creates an external magnetic field (H), and a pick-up coil (1.535.10—3 m^2) measures the magnetic induction (B) surrounding the sample. A total of four magnetic inductions ranging from 0.7 Tesla to 1.5 Tesla were applied to each sample. The experimental data of magnetic flux density (B) and magnetic field strength (H) were obtained using an NI USB-6259 board from National Instruments and custom software written in the Labview programming language. The hysteresis loops were constructed using these experimental data. These loops provide values of the coercivity performance, remanence, permeability, and power losses.[16]

One of the researches into annealing was to investigate the impact of annealing temperature and duration on the mechanical, magnetic, and microstructure characteristics of a low Silicon content, ultra-low Carbon content, and hot rolled steel with 0.05% Carbon, 0.57% silicon, and 0.21% aluminum. The initial hot-rolled microstructure is consumed by the aberrant anisotropic development of surface grains brought on by heat treatment. The grains start developing in opposing directions from the surfaces which affects the central part of the strip, they first grow parallel direction of the rolling and then later into a columnar from a parallel direction to the normal one. Research indicates that microstructures created by cold rolling followed by a brief annealing treatment at 700–800 °C can reduce iron energy losses in a material by up to 30% when compared to the same material that did not undergo the annealing process before cold rolling. The processing parameters and strip thickness determine how much energy is lost. The material that is processed through annealing at 983 K has the largest effect, and as strip thickness lowers, the overall relative effect diminishes. The effect has been considered on annealed material in comparison to the material that is not passed through annealing before the cold rolling process. It is demonstrated that these effects are related to how the texture and size of grains are affected by the processing conditions. When the final microstructure has ferrite grains that are larger approximately about 1.5 times than what would be obtained if the material is not annealed before cold rolling, the greatest reduction in energy losses is seen.

Even though it is commonly known that cutting can have a significant impact on electrical steel's magnetic characteristics, it is still unclear how to effectively assess these impacts on a prototyped machine's final shape, particularly when operating at a high frequency or high-power rating. This study offers a more useful technique for precisely measuring magnetic losses in electrical steel while taking the impacts of material deterioration from cutting into account. These examinations are carried out on an entire electrical machine core, as opposed to only a few laminations, as in other similar studies. Since back lack bonding is the least harmful connecting method, it is employed for lamination stacking to ensure a fair comparison between the two scenarios. The steel performance is measured using two distinct test rigs across a broad frequency and input power range. Electrical machine designers face additional difficulties as a result of the global movement to reduce energy use. A large portion of losses come from losses in the core, particularly in machines that are powered by PWM inverters and run at a higher rotational speed. Taking material degradation from mechanical or laser cutting into account is one of the key issues in core loss calculations.

2.5 Different doping schemes in electrical steels

In the ongoing research into electrical steel, the author has considered the impact of various doping strategies on the temperature dependence of broadband magnetic losses in Mn-Zn ferrites.[17]. TiO_2-doped pre-fired powders are mixed with increasing amounts of CaO, Nb_2O_5, ZrO_2, and SiO_2. The resulting ring samples are then evaluated vs frequency f (DC-1 GHz) and peak polarization Jp (2 mT – 200 mT) up to temperature 433 K after sintering at either 1548 K or 1573 K. It has been demonstrated that appropriately increased impurity levels can further reduce energy loss in materials that are already optimized for high-temperature operation (140–160 °C). This tendency is more closely linked to a similar monotonic reduction of the effective magnetic anisotropy compared to the extra-doping-induced impurity-related increase in electrical resistivity.[17]

Using traditional solid-state processing, four batches of manganese zinc ferrites with compositions of 71 weight percent Fe_2O_3, 23 weight percent manganese oxide, and 6 weight percent zinc oxide O were created. Oxides of high purity for raw materials (Fe_2O_3) from the supplier Thyssen-Krupp. The materials zinc oxide and manganese oxide of analytical grade, supplied by Merck, were weighed into the proper proportions and heated to 850 °C for four hours. Water was used as the suspension medium and dopants were added before the steel balls in steel vessels were milled for nine hours.

After the powder was dried at 90 °C for 24 hours and sieved where particle sized to 0.56 ± 0.05 μm, roller compaction was carried out with 0.2 weight percent polyvinyl alcohol. It acts as a binder. Uniaxial pressing was used to compact toroidal samples to an average density of 2.90 ± 0.02 g/cm3. The compacted specimens were sintered for three hours at either 1573 K or 1548 K in specially designed kilns, where the oxygen pressure is regulated using the Morineau and Paulus equation. This process produced complete ferrite production. The flowchart in Figure 2 illustrates the preparatory steps. The final ring examples have an inner diameter of 9 mm and an outside diameter of 15 mm, measuring around 5 mm in height. X-ray examining the crystal structure of the material where sintered specimens are explored. It verified that all samples taken for testing were pure spinel phases, whereas pre-fired powders showed changes after diffraction. The primary nuclei had been produced across the pre-firing step. According to the SEM examination, from D1 to D4, the average grain size marginally increased[(17)].

At all temperatures, increased doping has been demonstrated to favor energy loss reduction to some extent. However, the long-term impact of doping on mechanical durability varies depending on the additives used. Fe nanoparticles aid in the steel's improved texture development and grain size refinement. Refinement of grain boundaries lowers the possibility of undesired grain growth by improving control over grain orientation. Better mechanical qualities, like as strength and resistance to deformation, are directly mapped to the grain structure. In order to produce the correct grain structure in electrical steels, secondary recrystallization must be inhibited by TiO_2 particles. TiO_2 helps improve the mechanical endurance of the material by regulating grain formation, especially by increasing its resistance to brittleness, fatigue, and wear over time[(17)].

Using nanomaterials like Fe nanoparticles or TiO_2 can significantly reduce core losses in grain-oriented electrical steels, especially in high-efficiency electrical applications like transformers. There may be trade-offs in other material qualities, even when the advantages in terms of reducing core loss are significant. Enhancement of magnetic domain refinement is facilitated by the reduction of core loss. The hysteresis loss is reduced by the smaller particle sizes and finer domain topologies. Grain boundary inhibitors, such as TiO_2, function as additives during the annealing process. This enhances the grain alignment in the (110) plane, which is perfect for reducing core losses in GOES. Reduced magnetostriction and energy dissipation during the magnetization cycle are caused by the improved grain structure, which further reduces core losses. The use of nanoparticles can frequently increase a material's thermal stability. Nanomaterials such as TiO_2 prevent grain coarsening at high temperatures by refining the structure and limiting grain growth, therefore preserving the material integrity during high-temperature processes. By acting as passivation layers, these nanoparticles prolong the material's life, particularly in severe settings, by keeping the underlying steel from oxidizing.

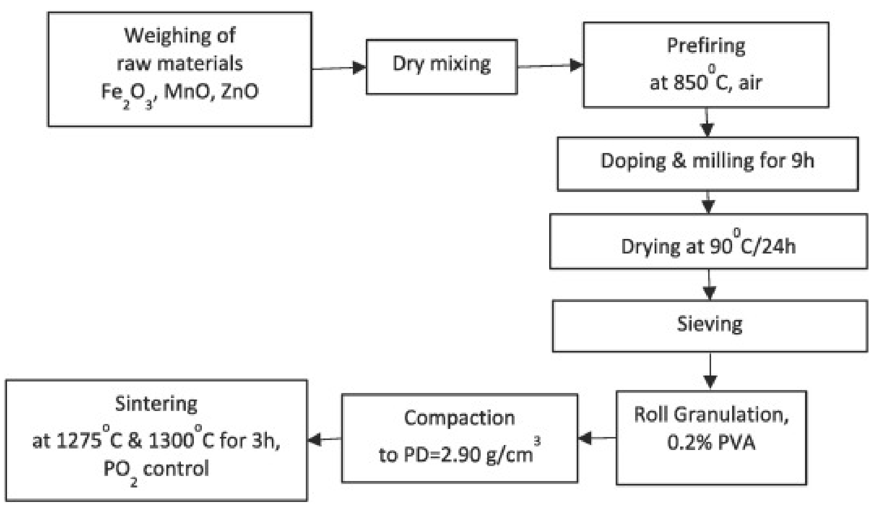

Fig 2. Flowchart of Mn-Zn ferrites processing[(17)]

3 Overview

Results and Findings

3.1 Inclusions and their impact on magnetic behavior

Figure 3 displays the results from the vibrating samples magnetometer (VSM). It is obvious that alloys with Ce addition have better magnetic characteristics than alloy 0#. The M—H curve was differentiated to obtain the magnetic susceptibility curves, which were then plotted against each alloy's permeability gap to provide a clearer visual representation. The greater permeability of alloy 2# is evident from the fact that its χ_{max} is the highest.[12]

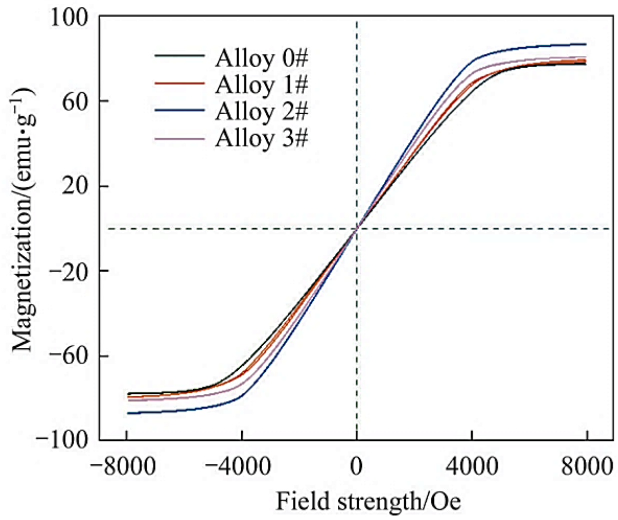

Fig 3. M-H graph of Iron-Nickel alloy[12]

The correlation between magnetic characteristics and inclusion count is depicted in Figure 4. Figure 4 illustrates how the coercivity of alloy 0# is 3.67 Oe, but as Ce is added, it drops to 3.58 Oe in alloy 2#. Furthermore, the greatest value of χmax, which indicates a 28% increase, is 0.0222 in alloy 2#, while it is 0.0173 in alloy 0#. Furthermore, a notable improvement in magnetic permeability along with a critical performance metric for ferromagnetic materials is indicated by the increase in χmax. Furthermore, Figure 4 demonstrates that the magnetic characteristics and inclusion count are correlated. When the quantity of inclusions diminishes, coercivity also diminishes, and χ_{max} rises.

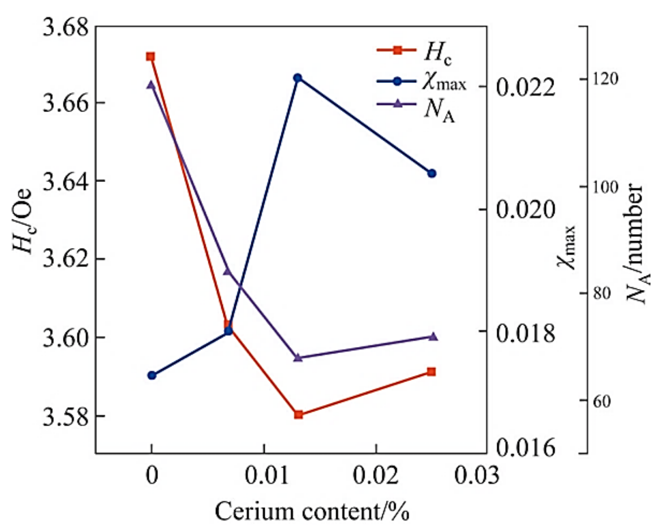

Fig 4. Graph of inclusions vs magnetic properties[12]

It is possible to explain the connection between the inclusions and magnetic characteristics. It may be inferred that permeability is dependent on the presence of precipitates that obstruct wall movement; the most harmful precipitates are oxides and sulfides, which are smaller than the thickness of the wall (<1 μm). Furthermore, the concentration of the inclusions, which are known to be harmful to both the domain wall's movement and the formation of the grains, affects the initial permeability of the permalloy. Overall, permeability is negatively impacted more by small inclusions (<1 μm) and becomes less as the number of inclusions increases.

The first hot-rolled microstructure of non-oriented electrical steels typically has a significant impact on the subsequent cold-rolling and annealing microstructure and texture development, as well as the ultimate magnetic characteristics. The literature describes the fabrication of three steel slabs with varying weight percentages of Al (0.41, 0.30, and 0.21 wt%), followed by hot rolling, cold rolling, and annealing on an industrial manufacturing line. Remarkably, it was discovered that in the hot rolled sheets with a minor decrease in Al, the highly elongated deformed grains were minimized or perhaps completely avoided. Larger grains were therefore produced as a result of cold rolling and annealing. As a result, the magnetic properties with higher magnetic induction and lower iron loss were greatly enhanced.

3.2 Compressive stress over electrical steel and its magnetic properties

The permeability was computed using the different rising hysteresis branches or moving from a negative to a positive value of the magnetic field, in which it attains the maximum value of the magnetic field each time, in order to make the visualization of σ influence on hysteresis loops easier to understand. Based on several compressive loads, sample A's differential permeability can be determined using Figure 5. Samples B and C behave similarly in general and won't be displayed. Figure 5 illustrates how differential permeability intensity diminishes with increasing compressive stress and shifts the maximum position of the magnetic field to higher fields. Electrical steel, both oriented and non-oriented, has previously demonstrated similar behavior. During the magnetization process, magnetoelastic energy and magnetic potential energy compete with one another. This behavior is known as the Villari effect [13].

The rotation of magnetic domains may be possible only if the external magnetic field, exceeds the sum of the uniaxial anisotropy that may be intrinsic or extrinsic. This is stated above. The domain structural pattern changes about 4-6 MPa to minimize the system's overall energy. This magnetic field (external) is referred to as the "critical field" (HCr) and is defined as the magnetic field that generates the largest value of permeability. It is crucial to stress that the stress pattern I is not generated and that this value cannot be regarded as HCr for compressive loads less than 6 MPa. Figure 5 displays the μ (mean) and σ (standard deviation or S.D.) of the value of the critical field at 1.7 Tesla and frequency of 60 Hz because every sample was examined in triplicate.

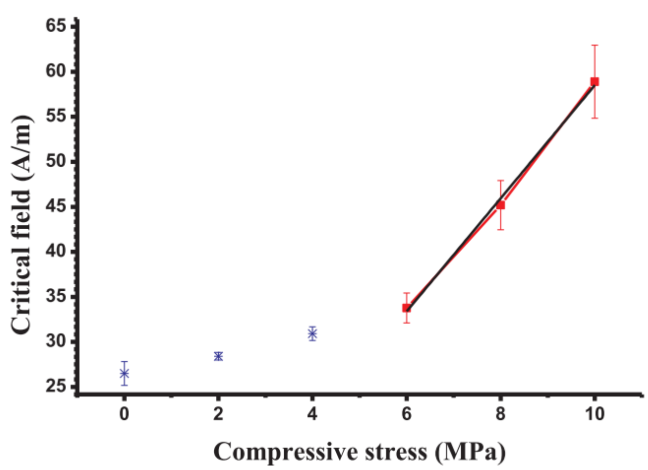

Fig 5. Compressive stress vs critical field (A/m) at 1.7 T and 60 Hz [13]

3.3 Influence of phase distributions on the macroscopic magnetic properties:

As per the texturing of hot rolled steels, a major variation in both grain size and grain orientation was found. The thickness direction showed a distinct gradient that could be separated into the central layer and the surface layer according to their respective properties. Fine equiaxed grains with a size range of 10 to 50 μm, generated during dynamic recrystallization, dominated the surface layer. The inclination of these grains with respect to the rolling direction was about 45°. The coarse and flattened distorted grains, ranging in width from 50 to 100 μm, were the defining feature of the core layer. The unequal distribution of deformation and temperature was the main cause of the microstructure heterogeneity along the ND direction.

Due to higher deformation and lower temperature, a higher density of dislocation occurred on the surface of the material, which acted as a catalyst for dynamic recrystallization. The lattices, {112} <111> (Copper) and {110} <112> (Brass) components dominated the texturing. As a result of the middle layer's primarily mild plane deformation, the recrystallization driving force was less strong. As a result, recuperation took center stage and the elongated state was maintained. In the meantime, textures of α-fiber and discontinuous γ-fiber were noted. The highest intensity was noted at around {100} <110> (f(g) = 7.31).[14]

After normalization, the microstructure's original gradient distribution almost vanished, and the size of the grain obtained was roughly 220 μm. In the surface layer of the original HRS, the coarse but equiaxed grains showed a worse coordinated deformation capacity than the fine grains, resulting in uneven deformation. The variation in grain size had a major impact on how the microstructure and texture changed in the processes that followed.

The magnetic characteristics of annealed sheets are shown in Figure 6. The iron loss for the annealed sheets originating from both pathways, P15/50 and P10/400, gradually decreased as the temperature in annealing rose from about 973 K to 1273 K. Interestingly, after annealing at various temperatures, the final annealed sheets from Route II had better magnetic characteristics. Large IGS annealed sheets lost less iron than the other annealed sheets after 1000 °C of annealing. P15/50 and P10/400 were reduced to 2.6 W/kg and 16.337 W/kg, respectively, from 3.2 W/kg and 17.695 W/kg, or 17.7% and 7.6%, respectively. After annealing at 900 °C, magnetic induction B50 increased by 3.3% from 1.664 Tesla to 1.719 Tesla in Route. This was its maximum value. It suggested that recrystallization of microstructure and texture could be optimized using normalization through raising IGS, leading to improved magnetic properties, considering the relationship between IGS and magnetic characteristics.

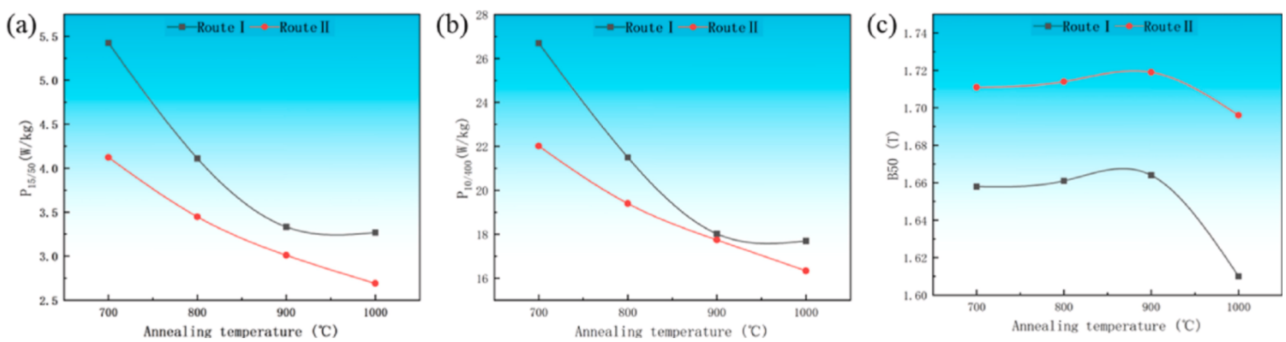

Fig 6. Different annealing temperatures show magnetic properties [14]

3.4 Relationship between annealing processes and the resulting magnetic behavior of electrical steel

The annealing process under low temperature and stress or magnetic field (AS) can be used to introduce an extrinsic magnetic anisotropy in ferromagnetic materials. During heat treatment, mechanical tension or a magnetic field are applied as part of these treatments. The results of this process are linked to the diffusion of silicon pairs at short range, which are solute. An elastic strain of crystal lattice results from the application of a magnetic field. If the temperature is high enough to promote atomic diffusion, the silicon pairs may reorganize themselves to relieve the stress by shifting their direction so that it aligns with the AS's mechanical stress/magnetic field direction.[16]

Sample A400(1)'s hysteresis loops at a range of 1.5 and 1.7 Tesla at AR and AS conditions are shown in Figure 7**(a)**. The AS impacts for the two samples were comparable and won't be displayed. The coercive field (Hc) reduced and the permeability (μ) increased after the AS, whereas the remanence (Br) remained almost unchanged in both circumstances. As a result, the hysteresis loops were found to be smaller for AS conditions than the AR for all the tests conducted for magnetic induction, which lowers the GOES material's power loss. The presence of the lancet domain is expected given the misaligned grains in sample A. As a result, certain Silicon pairs will line up at [1 0 0] and [0 1 0], or perpendicular to the direction of rolling. Tensile stress application during the AS causes the lancet domain volume fraction to decrease and solute pairs are reoriented to align with the rolling direction. This results in the permanent introduction of extrinsic magnetic anisotropy, which facilitates the magnetization process. It is crucial to emphasize that, even for misaligned grain that is, grains with an angle of up to 10° between the rolling direction and the Goss texture a tensile stress of 40 MPa is sufficient to eradicate all lancet domains. Following the AS, the power loss reductions are 18.5% $\pm$ 2.4, 16.2% $\pm$ 0.3, 8.5% $\pm$ 2.7, and 3.3% $\pm$ 0.3 at 0.7 Tesla, 1.0 Tesla, 1.3 Tesla, and 1.5 Tesla, respectively.[16]

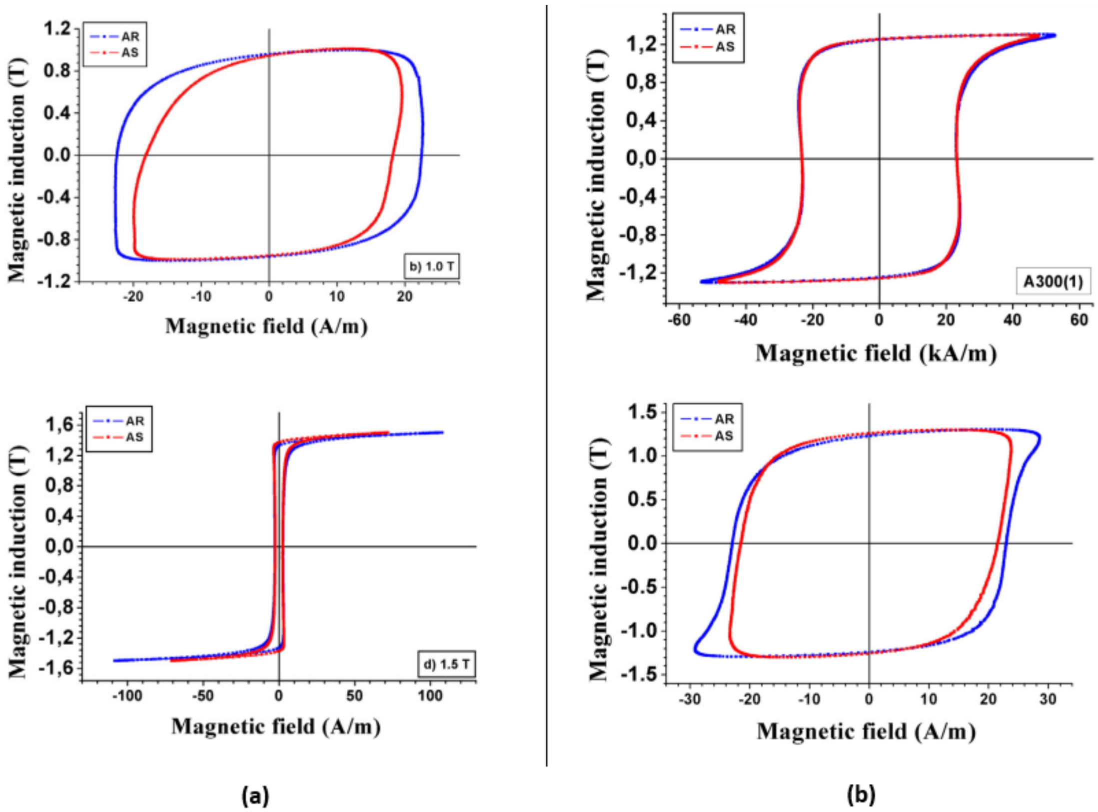

Fig 7. Hysteresis loops Blue loop indicates before low-temperature annealing Red loop indicates after low-temperature annealing: (a) sample A400(1) at 1.0 Tesla and 1.5 Tesla. (b) Sample A300(1) and B400(1) at 1.3 Tesla [16]

The AS scarcely modifies the hysteresis loop (Figure 7**(b)**) and magnetic characteristics of B400 samples, despite the fact that the x at 673 K is higher than the value at 573 K; as a result, the power loss reduction was only 4.8%. It is reasonable to assume that the extrinsic magnetic anisotropy intensity of the two samples is identical because the AS parameters stress 40 N/mm^2, temperature 673 K, and duration 20 min were the same as those of A400 samples. It implies that the extrinsic magnetic anisotropy intensity could be altered by a new parameter in addition to the standard AS parameters.

The exact degree of the core losses of two distinct samples of the case study SRM are measured using two separate setups that are constructed. A few NO20 un-joined laminations that have been laser-cut make up the first example. Testing is done on this sample using a low-power and low-frequency configuration. The second sample is a full stack stator constructed from identical laminations, but it also incorporates backlack bonding as an extra non-destructive stacking technique. The complete axial length core is then evaluated using a higher power rating test system, enabling it to be tested at greater frequencies and excitation currents. The additional core losses resulting from the laser cutting procedure are extracted independently for each of the two samples by comparing the outcomes. Furthermore, for the constructed machine, the total additional core losses as a result of the overall material degradation are precisely calculated. The magnetic characteristics of electrical steels that are not orientated are enhanced by a custom-made microstructure, particularly with regard to grain size and texture. Exact control over production and processing is one method of modifying the microstructure. Approaches such as modeling and simulation can be used to assess the effects of various process parameters and ultimately choose the right ones[18].

The magnetic characteristics of electrical steel are greatly influenced by temperature, which is frequently the case when operating electrical steel cores in electric motors. Variations in silicon content also lead to variations in the performance characteristics of electrical steel. In order to study the magnetic property variation of non-oriented electrical steel sheets with varying Si concentrations at varying temperatures, an environmentally adjustable electrical steel magnetic property testing equipment is constructed. It is discovered by research from the literature that the trend of electrical steels' magnetic characteristics tends to level out as Si concentration rises in response to temperature. Specifically, the 6.5% Si loss has a temperature-dependent trend that initially decreases and then increases.

3.5 Different doping schemes and their impact on magnetic losses in electrical steels

The findings and the examination of the permeability behavior in relation to Jp and f are reflected in the power losses for Jp of 2 mT to 200 mT, which goes up to 1 GHz. The difference in the contributions of eddy current loss in samples with thicknesses of 1.77 mm and 5.02 mm is indicated by the variations of the W(f) curves at around a frequency of 5 MHz. Along an overlapping frequency range, we also see the extra loss resulting from the magnetic aftereffect at a very low frequency (Jp = 2 mT) and then combine the VNA W(f) and flux metric curves, where the latter is acquired at a fixed power of 10 mW, which inevitably shrinks with increasing Jp. This demonstrates that the dws will eventually be entirely damped in with respect to rotations, regardless of Jp in high-frequency motion.[17]

The systematic analysis conducted across a broad matrix of (Jp – f) coordinates substantiates a definite tendency in the reaction of the doped samples. a. Extra-doping up to 50 parts per million (ppm) silicon results in a specific decrease of $< K_{eff} >$ at all temperatures (comparing two samples), according to the μrot study. As a result, we anticipate a positive impact on W(f) if Wdw(f) is significant, which occurs at medium frequencies and high enough Jp levels. The suggested three extra-doped samples show usually decreased power loss with respect to the conventional material D1 under these conditions, as shown in Figure 8.

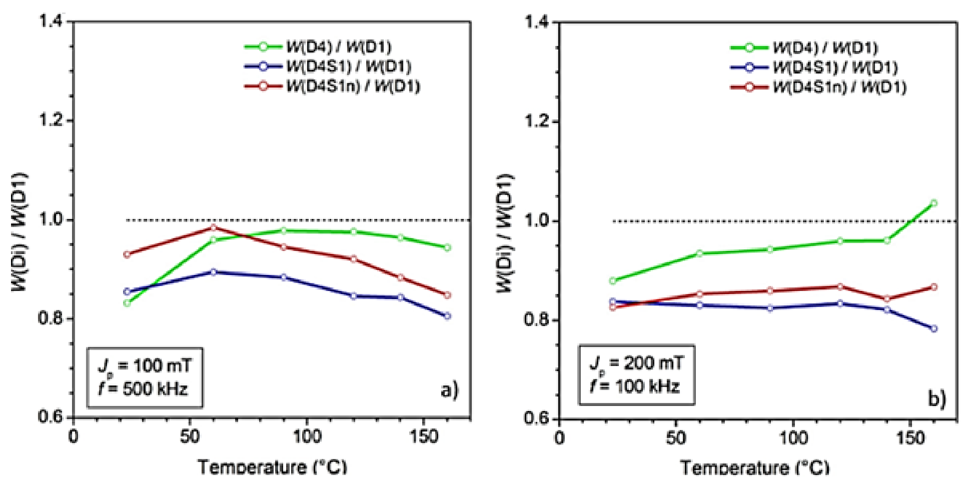

Fig 8. At Peak polarization Jp (at higher value), the dw contribution Wdw(f) to the observed loss[17]

In these conditions, the extra-doping in both samples seems to have a positive impact on the material characteristics compared to the initial standard ferrite D1, resulting in a 20% decrease in W(f).

on the creation of a method for computing efficiently determining eddy current losses that can be used in design optimization, particularly in cases when both the thermal and electromagnetic behavior of the machine are taken into consideration. Because of its increased leakage flux and opening fringing flux in slots, which are the main causes of eddy current losses in the windings, a permanent magnet synchronous machine is selected for this investigation [B]. An examination of the impact of electrical loading on ac winging loss effects for this machine design, is a topic that has not gotten as much attention in the literature. The outcomes exhibited strong concurrence with the findings from a TS-FEA incorporating comprehensive coil modeling, spanning an extensive spectrum of loading scenarios and operating frequencies. Meanwhile, by employing the suggested approach, the necessary computation time was greatly decreased. The losses in this case study machine were used for a future thermal performance analysis to highlight the significance of integrating eddy losses as a primary component of loss in high-speed machines.

The typical motor core composed of non-oriented silicon steel has a lower saturation magnetic density because of its silicon component. The need for current motors to have high torque densities and power densities is getting harder to meet. For the aforementioned reasons, suggested using a combined design to replace the non-oriented silicon steel core with the Grain-Oriented (GO) steel core portion. In the literature, a new thin an-isotropic GO silicon steel core for high-speed (up to 14500 rpm) traction motors is primarily presented[19].

Nowadays use of the Additive manufacturing process plays a vital role in research activities. Typically, the electrical machine cores are layered using soft magnetic laminations that have been varnished. This reduces eddy and hysteresis losses while the machine is operating. Currently, industrial-grade homogenous material metal components may be produced using specialized metal printing platforms, which facilitates the construction of machines with extremely complicated topologies. However, because these components lack laminated structure, this leads to an increase in induced eddy current. The 6.5% Si content samples showed more resistivity than any of the 3% content samples, indicating that the material would result in less eddy currents in machines made of it.

4 Conclusion

The review paper highlights the importance of staying informed about the latest developments in the magnetic properties of electrical steel. The magnetic characteristics are improved by the ce addition. The alloy with ce has the most advantageous magnetic characteristics as a result of the coercivity decreasing and permeability increasing. Furthermore, a correlation between inclusions and magnetic characteristics was discovered. Hysteresis loops are significantly impacted by compressive stress, which causes the differential permeability to decrease with increasing compressive stress. The investigation on the effect of grain size on magnetic characteristics after annealing using Route II was found that the sheets produced had better magnetic properties than the annealed sheets generated by Route I due to optimization of grain size and texture. The results showed that the minimum iron loss was P15/50 = 2.69 W/kg and the highest magnetic induction was B50 = 1.719T. Because there is more residual stress relaxation at higher temperatures, annealing can reduce hysteresis losses more successfully, which helps to simultaneously improve permeability and core losses. Hysteresis losses dominate the total core losses within rather wide frequency ranges that depend on annealing temperatures, according to loss-separation calculations. However, the substantial major effects of eddy-current at the region of higher frequency will produce drastically increased core losses and somewhat it may lower frequency stability of permeability for the steels annealed at 800 °C, because of degraded silicone-resin coatings[20].

A thorough magnetic characterization has been carried out, together with measurements of the complicated electrical resistivity, from DC to 1 GHz and up to 160 °C. At all temperatures, it is demonstrated that increased doping with CaO, Nb_2O_5, ZrO_2, and $SiO_{particles}$ favors loss reduction to some extent. After computation, it is demonstrated that the effective magnetic anisotropy < K_{eff} > monotonically decreases with T, having different impacts on Wdw(f) and Wrot, sd(f). Due to the local resonance frequencies, the rotational losses constantly rise with T. Elevated doping seems to have an indirect impact on < K_{eff} > and cause a moderate (20–30%) decrease in W(f) at all temperatures within the relevant (Jp–f) domain. The distribution of texture is influenced by a number of parameters, including the chemical makeup of steel, phase transformation, solidification cooling rates, directed solidification, recrystallization annealing, deformation regime, and others. However, texture evolution management during heat treatment and casting processes is complicated, and future study needs to continue addressing the mechanisms involved, especially for novel industrial processing pathways like strip casting.

Future Research Directions: There are ongoing challenges and opportunities in the field, including the development of nanomaterials, advanced coatings, and advanced alloy compositions. Researchers are also exploring innovative applications for electrical steel in the evolving energy landscape.

1. Use of Multi-material selective laser printing (SLM): At the moment, selective laser melting technology is not appropriate for reducing eddy currents through laminated structures because it is difficult to print different materials in parallel with distinct thermal behaviors and because the process is powder bed based, meaning that only one powder can be used at a time.

There are some challenges with utilizing SLM. It has not been possible to print insulating compounds alongside metallic materials using this technology. There are various applications including magnetic couplers and synchronous machine rotors that involve a quasi-static magnetic field is unaffected by the absence of insulating layers in SLM produced by soft magnetic materials. It is inadequate for employment in stator constructions, due to the significant eddy current created in the non-laminated structure by the rotating magnetic fields, resulting in reduced efficiency. It also gives excessive thermal heating of the machine. It has been demonstrated that finite internal material structures with geometric manipulation are possible when using the spatial accuracy of additive manufacturing techniques and that this significantly lowers the creation of classical eddy currents. However, adding air gaps lowers the material filling factor as well. As a result, oversaturation would be necessary to provide the same flux as in a laminated or totally dense construction[21] .

Recent advances in powder deposition technology, which allow for the selective powder deposition of several materials, imply that multi-material SLM printing of electromechanical components may become feasible soon. Currently, it is proposed that geometric manipulation that is, printing materials with refined internal structures can reduce eddy current losses in printed components. One can either print the material as a dense lattice structure or introduce air holes into it perpendicular to the direction of the flux to achieve material evolution[21].

2. Machine Learning and Materials Modeling: There is a huge scope nowadays for computational materials science, machine learning, and artificial intelligence which can be used to predict and optimize the properties of electrical steel. These tools can assist in designing materials with specific characteristics and identifying novel alloy compositions. In order to correlate the microstructural characteristics of steels during secondary recrystallization with their magnetic losses which were ascertained from hysteresis loops a machine learning-based method was developed. The literature overcame the inadequate database

and imbalance between classes by applying a certain methodology to produce synthetic samples. To the best of the authors' knowledge, no prior study has approached this problem in this way. Usually, costly and time-consuming tests are used to investigate the magnetic losses of NGO steels. Using real data, the Least Squares Support Vector Machine (LSSVM) produced the best results, with an accuracy of 88.9% [(22)].

Machine learning computational algorithms can help develop an easy, quick, and automatic correlation between the magnetic losses, which are derived from the hysteresis curves, and the microstructural conditions, which rely on the temperatures employed in heat treatments. An innovative method based on machine learning techniques is developed to automatically link the various secondary recrystallization stages in steels to the corresponding hysteresis cycles. Here, the hysteresis cycle measurements from electrical steel samples are used as features in a pattern recognition problem to address the secondary recrystallization states as classes. The suggested method was assessed by the author using a number of cutting-edge machine learning classifiers in extensive computer tests [(22)] .

An algorithm for identifying aberrant magnetic fields and losses in silicon steel sheets (SSS) is explained in the literature. The measured hysteresis field is used to extract the anomalous magnetic field, which is separated from the static hysteresis and eddy current fields. This is because the magnetic field in an SSS is made up of these three components: eddy current, static hysteresis, and anomalous magnetic fields. To forecast the anomalous magnetic field for every given B-waveform, a deep learning algorithm-equipped artificial neural network model is proposed [(23)].

In an experiment, the magnetic fields of ordinary and grain-oriented sheets taken to particular surface engineering techniques were assessed using a combination of Magnetic Barkhausen Noise and many machine learning techniques. The analysis that is being presented was carried out to evaluate the effectiveness of two machine learning techniques, deep learning (DL) and traditional ML, with regard to the identical examination problem and using the database [(24)].

Literature uses the energy landscape produced by machine learning to explore the magnetization process at high frequencies. By utilizing a blend of machine learning and topological data analysis (TDA), we are able to examine the ways in which microstructures affect magnetization at frequencies ranging from 1 to 100 kHz. Within TDA, a technique called persistent homology (PH) converts these domains' intricate topological properties into vectors that can be examined. This procedure offers a thorough research of material properties under high-frequency circumstances by enabling a thorough examination of the magnetic properties and how they vary with frequency. We were able to connect the topological elements to the anomalous eddy current loss and assess the energy loss by looking into the PCA elements [(25)].

3. Recycling: The recycling of electrical steel, especially with specialized coatings and alloys, can be complex. Improving the recyclability of electrical steel and reducing waste in the production and end-of-life phases is a priority.

4. Nanomaterials Scaling: While nanostructured electrical steel shows great promise in terms of reduced losses and enhanced efficiency, scaling up the production of these materials for industrial use remains a challenge. It requires significant advancements in manufacturing techniques.

5. Loss Reduction in Specific Applications: Achieving significant loss reduction in certain applications, like high-frequency transformers or very compact electrical devices, can be particularly challenging due to the limitations imposed by size, shape, and material constraints.

6. Advanced Alloy Formulations: Researchers can explore novel alloy compositions to tailor electrical steel properties for specific applications. This includes developing alloys with enhanced magnetic properties, reduced losses, and improved mechanical strength.

7. Standardization and Testing: The establishment of consistent testing methods and standards for electrical steel properties can be a challenge. Standardization efforts are important for quality control and ensuring reliable performance.

These areas for future research and development have the potential to advance the field of electrical steel, leading to more efficient, sustainable, and versatile materials that meet the evolving needs of modern electrical systems and devices. Collaboration between academia, industry, and regulatory bodies will be crucial in realizing these advancements.

In conclusion, staying informed about the latest developments in electrical steel research is essential for improving energy efficiency, reducing electrical losses, and advancing sustainable technologies. It has a significant impact on multiple industries and contributes.

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