

Influence of Annealing Treatment on Electrical Steel Characteristics and Electric Machine Performance

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Abstract

This study experimentally investigates the effect of two annealing routes on the magnetic, core-loss, and electrical characteristics of electrical steel used in a BLDC Motor. Three conditions were evaluated: Sample A subjected to a multi-stage controlled annealing process, Sample B subjected to a high-temperature rapid annealing process, and Sample C retained in the as-cut condition as the untreated reference. Compared with Sample C, Sample A showed a 2.44% increase in B_{rms} , a reduction in H_{rms} , and an increase in permeability. Sample B produced a comparable improvement of 2.20% in B_{rms} at 50 Hz and 1.5 T. The average core loss decreased from 5.90 W/kg for Sample C to 4.90 W/kg for Sample A and 5.10 W/kg for Sample B. The line inductance increased from 104.90 μ H to 109.38 μ H and 107.15 μ H, respectively, while winding resistance remained nearly unchanged. The short-circuit current decreased from 52.36 A for Sample C to 48.15 A for Sample A and 49.85 A for Sample B. These results demonstrate that annealing significantly influences the magnetic and electrical behaviour of the BLDC Motor core.

1 Introductions

1.1 Significance of the Research

Electrical steel is everywhere in our modern world. It forms the magnetic cores of power transformers that distribute electricity to our homes, electric motors in everything from industrial machinery to household appliances, and countless other electromagnetic devices. Owing to its strong magnetisation and demagnetisation behaviour, non-oriented electrical steel ranks among the most widely used soft magnetic materials in industrial applications, commonly serving as the core material in motors and small-scale transformers [1]. As global energy efficiency standards become stricter and environmental concerns grow, reducing energy losses in these materials has become critically important. Impurity content was shown to elevate iron loss both directly, by interfering with magnetic domain behaviour, and indirectly, through its influence on grain size and crystallographic texture. Advances in clean-steel manufacturing subsequently enabled substantial reductions in core loss [2]. The manufacturing processes and technologies of electrical machines can significantly affect their performance [3] [4]. The numbers tell the story: the global electrical steel market was worth over \$12 billion in 2023 and is expected to double in value nearly. Magnetic cores inevitably lose some energy as heat. This happens in transformers humming on power lines and motors running in factories. While these losses might seem small, they add up to enormous sums across millions of devices worldwide. Even a modest percentage reduction in these losses can save massive amounts of energy and money over the decades these devices typically operate.

The iron and steel industry accounts for almost 18% of worldwide industrial energy consumption, and optimising manufacturing processes has become increasingly important. Even small gains in energy efficiency during electrical steel production can translate into considerable energy savings, lower operating costs, and improved overall process sustainability. [5]

1.2 Overview of Loss Phenomena in Magnetic Materials

For the analysis of frequency-dependent core losses, the Bertotti loss-separation approach was employed to decompose the total specific loss into three components: hysteresis loss, classical eddy-current loss, and anomalous (or excess) loss. This methodology is based on the different physical mechanisms responsible for energy dissipation in magnetostrictive materials. The total core loss density can therefore be expressed as:

$$p_v = p_h + p_e + p_a = k_h f B_m^\alpha + k_e (f B_m)^2 + k_a (f B_m)^{\frac{3}{2}}$$

1

where p_h , p_e , and p_a represent the hysteresis, eddy-current, and anomalous loss components, respectively. The parameters k_h , k_e , and k_a denote the corresponding loss coefficients, while f is the excitation frequency and B_m is the peak magnetic flux density. These coefficients are not constant and may vary with changes in operating frequency and magnetic flux density, reflecting the influence of material characteristics and magnetisation conditions on the overall loss behaviour [6].

To improve electrical steel, we first need to understand where energy gets lost. When alternating magnetic fields cycle through steel cores, several things happen simultaneously that waste energy:

$$P_{\text{total}} = P_{\text{hysteresis}} + P_{\text{eddy}} + P_{\text{anomalous}} + P_{\text{other}} \quad (2)$$

Each component has distinct causes; for example, hysteresis loss occurs when magnetic domains in the steel struggle to flip back and forth in response to the alternating field. Eddy current loss comes from unwanted electrical currents induced in the conducting steel. Anomalous loss is associated with complex magnetic domain behaviour that remains only partially understood.

The mathematical relationships governing these losses have been studied for decades, with the Steinmetz equation being particularly important for predicting hysteresis losses as functions of frequency and magnetic field strength.

While electrical steel exhibits low iron loss in its original form, this performance is often degraded once the material is shaped into a motor core. Manufacturing steps such as stamping and shrink fitting subject the steel to significant mechanical stress, which locally alters its magnetic characteristics and drives up iron loss [7]. Since the steel sheets must first be stamped into the required core geometry and subsequently laminated using shrink-fitting, both processes introduce stress at critical stages of assembly, making them key contributors to the gap between the as-supplied material's performance and the final in-motor loss.

1.3 Influence of Heat Treatment on Steel Magnetism

Heat treatment (annealing) can dramatically improve electrical steel's magnetic properties through several mechanisms working together. The process involves carefully heating and cooling the steel to modify its internal structure.

During heating, the steel's microscopic grain structure rebuilds itself. Cold-worked steel contains internal stresses and deformed grains that impede magnetic domain movement. Heat treatment allows new, stress-free grains to form and grow to optimal sizes.

Carbon atoms, even in tiny amounts, act like roadblocks for magnetic domains. Heat treatment in the right atmosphere can remove these carbon atoms, making it easier for magnetic domains to move and reducing energy losses.

Manufacturing processes introduce internal stresses that make magnetic domains work harder to change direction. Proper heat treatment relieves these stresses, resulting in smoother magnetic behaviour.

The combined effects of temper rolling and final annealing, and the resulting changes, drive variations in magnetic properties such as core loss, magnetic induction, and permeability, as well as in residual stress and microstructure. [8]

1.4 Literature Review and Gap Analysis

Conventional wisdom suggests that higher temperatures and aggressive thermal treatment produce the best results. Most research on electrical steel annealing focuses on optimising single parameters, such as temperature or annealing time, rather than comparing entirely different approaches [8]. Improving non-oriented electrical steel for HEV traction motors centres on managing a fundamental trade-off: adding silicon lowers iron loss by increasing resistivity and reducing magnetic anisotropy, but it also weakens saturation magnetisation, since silicon is non-magnetic. Because silicon content alone cannot deliver both low loss and high flux density, manufacturers combine several approaches [9]. The performance is measured, and it is found that torque density can be enhanced when using annealed electrical steel [10].

Existing research investigates the influence of individual process parameters, such as annealing time and initial texture, on the magnetic properties of steel, specifically magnetic induction and core loss. Studies have demonstrated that increasing annealing time can reduce iron loss, while the initial Goss texture significantly affects magnetic induction and overall magnetic performance [11].

Previous studies have primarily investigated the influence of annealing parameters, grain size, texture evolution, and precipitate distribution on the magnetic properties and core losses of electrical steel. [12]. In contrast, the present research establishes a direct relationship between the complete annealing cycle and final motor performance.

However, these studies are largely limited to material-level characterisation and do not demonstrate how the complete annealing process affects the performance of the final electromechanical product.

Our research extends beyond conventional material studies by evaluating the effects of the complete annealing cycle on the entire motor system, rather than only on the properties of electrical steel.

Prior research has approached this challenge from multiple angles. Several studies have focused on identifying optimal treatment windows in the 800–825°C range, typically applied over 2–4 hours. In contrast, others have investigated ultra-rapid heating techniques, though these often face practical barriers to industrial adoption. Despite this body of work, a few key questions remain open:

However, several important questions remain unanswered.

1. How do fundamentally different annealing strategies perform when compared directly against one another?
2. What role does process consistency play in scaling these methods to industrial production?
3. Under what conditions might a "gentler" treatment outperform a more "aggressive" one?

Our work centres on evaluating the relative advantages of two distinct annealing methods, each suited to different application areas, with their own sets of trade-offs between benefits and limitations.

1.5 Proposed Research Approach

The study begins with the magnetic characterisation of two processed and one untreated electrical steel samples to evaluate their magnetic properties and loss characteristics. The characterised materials are subsequently wound into stator assemblies, and their electrical parameters, including resistance and inductance, are measured. Each stator is then coupled to a permanent-magnet rotor to form a complete machine assembly. Key performance parameters such as back electromotive force (BEMF), short-circuit current, and current rise rate (di/dt) are experimentally determined. A detailed comparative analysis is finally conducted to quantify the influence of material processing on magnetic behaviour, electrical characteristics, and overall machine performance, leading to conclusions regarding the optimal processing condition.

Comparative Study Design - Two Annealing Philosophies. At the core of this investigation lies a direct, head-to-head comparison between two annealing strategies that represent fundamentally different approaches to achieving the same end goal: restoring and optimising the magnetic performance of electrical steel after cold working.

Process A - follows a deliberate, multi-stage thermal profile, incorporating controlled ramp rates, intermediate holding steps, and gradual cooling. The underlying philosophy here is patience: by allowing the microstructure sufficient time to evolve at each stage, this method aims to promote uniform recrystallisation, minimise thermally induced stress gradients, and give grain growth a chance to proceed under near-equilibrium conditions. The trade-off is longer cycle times, which naturally raises questions

about throughput in a production environment. Figure 2 illustrates the temperature–time profile and sequential stages of the Process A annealing cycle.

Process B, in contrast, takes a more aggressive, single-stage route

rapid heating to a higher peak temperature, followed by a comparatively short hold and accelerated cooling. This approach prioritises efficiency and cycle-time reduction, making it attractive from a manufacturing throughput perspective. However, the compressed thermal window raises legitimate concerns about whether the microstructure has adequate time to reach a stable, homogeneous state before cooling locks it in. Figure 3 illustrates the temperature–time profile and sequential stages of the Process A annealing cycle.

Importantly, our objective in this study extends beyond simply ranking these two processes by average performance. While mean core loss or permeability values are useful headline metrics, they can mask a more practically important issue: *consistency*. A process that yields excellent magnetic properties on average but with wide batch-to-batch variability is of limited value on a production floor, where predictability and repeatability often matter as much as peak performance. Accordingly, this work evaluates both the central tendency and the variability of key magnetic properties across multiple samples for each process to determine which annealing philosophy offers not only stronger results but also the reliability demanded by real-world manufacturing conditions. This study directly compares two fundamentally different annealing philosophies.

Process A - A patient, multi-stage approach with careful temperature control.

Process B - A faster, high-temperature method focused on efficiency.

We wanted to understand not just which works better on average, but also which is more reliable and consistent, crucial factors for real-world manufacturing.

2 Experimental Design and Sample Preparation

2.1 Sample Allocation and Process Overview

The experimental campaign began with a batch of 9–12 electrical steel samples, partitioned to allow a balanced comparison across three conditions. Three to four samples were assigned to each of the two annealing routes under investigation, Process-A and Process-B. At the same time, a smaller subset was deliberately left untreated to serve as an as-received reference.

Detailed process parameters for each route are described in the following subsections. Once annealing (or, for the control group, no treatment) was complete, all samples proceeded to a common winding stage. To isolate the effect of the annealing treatment itself and avoid confounding variables, winding was carried out under strictly identical conditions across all groups, with the same number of turns, the same winding tension, and the same operator performing every winding operation. This level of

procedural control was essential, since even small inconsistencies in winding technique can obscure or distort differences in magnetic performance that are actually attributable to the heat treatment. Before winding, however, each unwound sample was sent to an independent external laboratory for characterisation, where its B-H curve and associated core losses were measured. Performing this testing before winding ensured that the reported magnetic properties reflect the intrinsic behaviour of the annealed (or untreated) steel itself, free from any influence the winding process might otherwise introduce. Figure 4 shows an overview of sample preparation and its details, including the stator stack with winding samples A (multi-stage controlled annealing), C (no annealing or untreated), and B (high-temperature rapid annealing).

2.1.1 Preparing the Steel Samples

All samples were sourced from commercially available non-grain-oriented electrical steel, consistent with grades typically employed in motor and transformer cores. To ensure that any observed differences in magnetic performance could be attributed to the annealing treatment rather than to inconsistencies introduced during sample preparation, all samples were fabricated using a stamping tool. This method was chosen specifically for its low mechanical stress footprint, avoiding the shear-induced deformation and edge damage that conventional punching or shearing can introduce, a factor that, if left uncontrolled, could easily mask the more subtle effects of annealing itself. Following cutting, each sample underwent a structured preparation sequence:

1. Cleaning—samples were thoroughly degreased and cleaned to remove residual oils, cutting fluids, and surface contaminants that could otherwise interfere with magnetic testing.
2. Visual inspection — each sample was examined for surface defects, burrs, or visible damage that might compromise measurement integrity.
3. Dimensional verification — precise measurements were taken to confirm that all samples shared identical geometry, eliminating dimensional variation as a confounding factor.
4. Baseline characterisation — initial magnetic properties were recorded before any treatment, establishing a reference point against which post-annealing changes could be meaningfully assessed.

Samples were then organised into three experimental groups -

1. Untreated group — left in the as-cut condition, with no subsequent heat treatment, representing baseline magnetic performance.
2. Process A group — subjected to the multi-stage, controlled annealing route described in Section 2.2.
3. Process B group — subjected to the high-temperature, rapid annealing route described in Section 2.2.

This three-way grouping structure was designed to allow not only a direct comparison between the two annealing philosophies, but also an assessment of each treatment's improvement relative to the

untreated baseline, providing a more complete picture of how each process influences the steel’s magnetic behaviour.

2.2 The Two Heat Treatment Methods

Process A: The Patient Approach

This method uses five carefully orchestrated stages. The Process: A cycle is shown in Fig. 2 and explained in Table 1.

Table 1
Process A - Multi-Stage Controlled Annealing Schedule

Stage	Description	Temp.	Duration	Purpose
1	Surface Cleaning	430°C	–	Removes surface contaminants; prepares steel for treatment
2	Pre-heating	450°C	120 min	Initiates stress relief; prepares material for higher temperatures
3	Primary Treatment	770°C	120 min	Recrystallisation and carbon removal (decarburization]
4	Controlled Cooling	Gradual ramp-down	–	Prevents thermal shock; optimises final grain structure
5	Natural Cooling	Furnace ambient → room temp.	–	Final cooling within the furnace environment

Process B: The Fast Track

This method uses three stages focused on efficiency. The Process B cycle is shown in Fig. 3 and explained in Table 2, respectively.

Table 2
Process B - Fast-Track Rapid Annealing Schedule

Stage	Description	Temp.	Purpose
1	Rapid Pre-heating	450°C	Quick heating for basic stress relief
2	High-Temperature Soaking	770°C	Extended high-temperature exposure for maximum effect
3	Controlled Cooling	Ramp down to room temperature.	Systematic cooling to room temperature

The key difference: Process A takes about 9.5 hours in total, while Process B takes about 6.5 hours.

2.3 Measuring Magnetic Properties

The most important analysis is to visualise the impact of the annealing processes through the B–H curve, as shown in Fig. 5. The B–H curves clearly illustrate the magnetic behaviour and saturation characteristics of the core materials under different processing conditions. The observed differences in the B–H characteristics also indicate that the annealing process influences the magnetic properties, which in turn affect the material's core-loss behaviour. A representative inductance and other parameter measurement setup is shown in Fig. 6

Magnetic measurements were performed using a Precision LCR Meter to characterise the electromagnetic behaviour of the electrical steel specimens under investigation. Toroidal core samples were prepared with uniformly wound excitation and sensing coils to facilitate accurate magnetic flux generation and measurement. All experiments were conducted under controlled environmental conditions to minimise the effects of temperature and humidity variations on the measured parameters. Furthermore, testing procedures were standardised, and repeated measurements were conducted to ensure data consistency, reproducibility, and statistical confidence.

The samples were characterised at 50 Hz and a maximum magnetic flux density of 1.5 T, which corresponds to typical operating conditions in electric machines and transformers. The selected test conditions enabled a direct comparison of the magnetic characteristics of the untreated and annealed specimens. They provided insight into the impact of the annealing process on material performance.

Table 3
Relative comparison of magnetic properties with the untreated Sample C as the baseline.

Type of Sample	<i>B</i> _{rms} (T)	Change	<i>H</i> _{rms} (A/cm)	Change	Permeability	Change
Sample C (Untreated)	1.230	0.00%	5.47	0.00%	1401	0.00%
Sample A (Process A)	1.260	+ 2.44%	3.51	−35.83%	2077	+ 48.25%
Sample B (Process B)	1.257	+ 2.20%	3.57	−34.73%	2053	+ 46.54%

2.4 Process Performance, Variability, and Consistency Analysis

To ensure the reliability and robustness of the experimental findings, a comprehensive statistical evaluation was performed on all measured datasets. Descriptive statistical metrics, including the arithmetic mean, were calculated to quantify the average performance of each sample group. The standard deviation was employed to assess data dispersion and process consistency, providing insight into the repeatability and stability of the measured characteristics. In addition, confidence intervals were calculated to quantify the uncertainty in the experimental observations.

Appropriate statistical hypothesis tests were conducted to verify that the observed differences in magnetic and electrical performance were attributable to the applied processing conditions rather than random experimental variation. This statistical framework enabled an objective and rigorous comparison of the material states investigated. Beyond absolute performance improvements, the consistency and repeatability of each annealing process were also evaluated. For industrial applications, a manufacturing process must not only enhance material properties but also ensure stable, predictable performance across multiple production batches. The analysis revealed a distinct trade-off between performance enhancement and process robustness.

Process A demonstrated superior magnetic performance and lower core loss; however, it exhibited greater variability among specimens, indicating greater sensitivity to process control parameters. In contrast, Process B produced highly consistent and repeatable results across all tested samples, although the resulting performance improvements were comparatively moderate. The differences in performance and variability can be attributed to the thermal profiles employed during annealing.

Table 4
Core loss measurements at 50 Hz and 1.5 T with untreated Sample C as the baseline.

Sample Group	Individual Measurements (W/kg)	Avg. (W/kg)	Std. Dev.	Coeff. of Var.	Change vs. C
Sample C (Untreated)	5.840, 5.967, 6.009, 5.866	5.90	0.075	1.27%	0.00%
Sample A (Process A)	4.818, 4.933, 5.048, 4.854	4.90	0.102	2.08%	-16.95%
Sample B (Process B)	5.048, 5.077, 5.195, 5.124	5.10	0.065	1.27%	-13.56%

Table 5
Comparison of electrical and short-circuit characteristics for different sample conditions.

Sample Group	Line Inductance (μH)	Resistance (mΩ)	BEMF (V)	Short-Circuit Current (A)	Rate of Change of Current (A/50 μs)
Sample C (Untreated)	104.90	38.70	4.73	52.36	3.91
Sample A (Process A)	109.38	38.74	4.99	48.15	6.86
Sample B (Process B)	107.15	38.75	4.82	49.85	5.49

The extended soaking period and staged cooling strategy shown in Fig. 2 are likely to promote more significant microstructural modifications, leading to reduced average core losses but increased process-induced variability. Conversely, the shorter and more uniform thermal cycle illustrated in Fig. 3 results in improved process stability and repeatability, yielding more consistent magnetic properties across the evaluated specimens. These findings emphasise the importance of balancing magnetic performance enhancement with manufacturing consistency when selecting an annealing strategy for industrial-scale production of electrical steel components.

Figure 7. presents the measured specific core-loss values for individual samples under the three investigated conditions: non-treated, Process A, and Process B. Four samples were evaluated for each condition, and all measurements were performed at 50 Hz and a peak magnetic flux density of 1.5 T under identical test conditions. The individual data points represent the sample-to-sample variation, while the box represents the interquartile range and the central line indicates the median. The relatively narrow distribution within each group indicates limited sample-to-sample variation under the selected measurement conditions. Process A shows a slightly wider spread than the non-treated condition, whereas Process B exhibits a comparatively compact distribution. Since the same measurement conditions and sample quantities were maintained across all three groups, the observed differences can be directly compared to evaluate the effect of each thermal treatment on core-loss characteristics. The individual measurements also confirm that the reduction observed in the annealed samples is consistent across the tested specimens, rather than arising from a single measurement.

3 Results and Discussion

The experimental investigation was conducted to evaluate the effects of two annealing routes on the magnetic properties, core loss, and electrical characteristics of the electrical steel core used in the BLDC Motor. Three sample conditions were considered throughout the investigation. Sample A underwent Process A, a multi-stage controlled annealing route. Sample B underwent Process B, representing a high-temperature rapid annealing route. Sample C was retained in the as-cut condition without any subsequent heat treatment and was used as the untreated control.

The experimental measurements were performed using the test arrangement shown in Fig. 6. The setup incorporates the dynamometer and associated electrical measurement instruments used to characterise the samples and evaluate their influence on the machine-level electrical response. The comparison was performed under equivalent test conditions to evaluate the effect of the core treatment relative to the untreated condition.

3.1 Annealing Processes

The two annealing routes were intentionally selected with different thermal-processing approaches. Process A employed a multi-stage controlled thermal cycle consisting of surface cleaning, pre-heating,

primary treatment, controlled cooling, and subsequent natural cooling, as summarised in Table 1. The primary treatment was conducted at 770°C following pre-heating at 450°C . The gradual thermal transition was intended to provide a controlled treatment environment and reduce the possibility of thermally induced non-uniformity.

In contrast, Process B employed a simplified rapid annealing route consisting of rapid preheating, high-temperature soaking, and controlled cooling, as summarised in Table 2. The process was designed to reduce the overall thermal processing sequence while maintaining exposure to the high-temperature treatment condition.

The comparison between these two processes is therefore not limited to the treatment's final temperature. The heating rate, thermal exposure, number of process stages, and cooling path are also different. Consequently, the measured magnetic and electrical properties provide an experimental basis for evaluating whether the simplified Process B can reproduce the characteristics obtained using Process A.

3.2 Magnetic Characterisation

The measured magnetic properties of the three sample conditions are summarised in Table 3. The untreated Sample C is considered the reference condition for evaluating the percentage change produced by the two annealing processes.

The untreated Sample C exhibited a B_{rms} of 1.230 T, an H_{rms} of 5.47 A/cm, and a permeability of 1401. Following Process A annealing, Sample A exhibited an increase in B_{rms} to 1.260 T, corresponding to an increase of approximately 2.44% relative to Sample C. At the same time, H_{rms} decreased from 5.47 A/cm to 3.51 A/cm, representing a reduction of approximately 35.83%. The measured permeability increased from 1401 to 2077, corresponding to approximately a 48.25% increase.

These changes indicate that the magnetic response of the electrical steel was substantially modified by Process A. In particular, the reduction in H_{rms} accompanied by an increase in permeability indicates that a lower applied magnetic field was required to establish the measured flux-density condition. The increase in B_{rms} was comparatively small, indicating that the principal change was associated with the magnetic response of the material rather than a large change in the measured flux-density level.

Sample B showed a similar magnetic response. The measured B_{rms} was 1.257 T, representing a 2.20% increase relative to Sample C. The corresponding H_{rms} was 3.57 A/cm, representing a 34.73% reduction relative to the untreated condition. The permeability increased to 2053, representing a 46.54% increase over Sample C.

An important observation is the close agreement between Samples A and B. The difference in B_{rms} between the two annealed samples was only 0.003 T, while the difference in H_{rms} was 0.06 A/cm. Their measured permeabilities were 2077 and 2053, respectively. Therefore, under the measured conditions,

Process B produced a magnetic response close to that of Process A, despite employing a different thermal-processing route.

This result is particularly relevant to the objective of reducing the thermal-processing burden while retaining the desired magnetic characteristics. However, the equivalence of the two annealing processes cannot be established from magnetic measurements alone. The electrical characteristics and short-circuit response must also be considered.

3.3 Core-Loss Characteristics

Core-loss measurements were conducted at 50 Hz and 1.5 T, and the results are presented in Table 4. The untreated Sample C exhibited an average core loss of 5.90 W/kg. After annealing in Process A, the average core loss decreased to 4.90 W/kg, corresponding to a reduction of approximately 16.95% relative to the untreated condition. Sample B exhibited an average core loss of 5.10 W/kg, corresponding to a reduction of approximately 13.56% relative to Sample C.

The reduction in core loss following both annealing treatments indicates that the thermal treatment had a measurable influence on the magnetic-loss characteristics of the electrical steel. Process A produced the greater reduction in measured core loss, while Process B also yielded a substantial reduction compared with the untreated condition.

The repeatability of the measurements can be considered using the coefficient of variation (CV). The reported CV values were 1.27% for Sample C, 2.08% for Sample A, and 1.27% for Sample B. The relatively low CV values indicate that the measurements within each sample group were reasonably consistent under the specified test condition. The slightly higher CV for Sample A indicates greater measurement-to-measurement variation than observed for Samples B and C. Therefore, although Process A produced the largest reduction in average core loss, the measured scatter should also be considered when assessing the process.

From an application perspective, the reduction in core loss is important because it directly affects the machine's magnetic loss component and can influence the core's thermal loading during operation. The present measurements demonstrate that both annealing routes yield a measurable improvement over the untreated condition at the investigated frequency and flux density.

3.4 Electrical Characteristics

The measured electrical and short-circuit characteristics are presented in Table 5. The untreated Sample C exhibited a line inductance of 104.90 μ H. Following Process A, the inductance increased to 109.38 μ H, representing an increase of approximately 4.27% relative to the untreated condition. Sample B exhibited a line inductance of 107.15 μ H, which is approximately 2.15% higher than the untreated condition.

The increase in inductance is consistent with the observed improvement in magnetic properties. Since the winding resistance remained nearly unchanged, the change in inductance provides an important

indication that the annealing treatment altered the core's magnetic characteristics rather than significantly changing the copper winding characteristics.

The measured resistance values were $38.70 \text{ m}\Omega$ for Sample C, $38.74 \text{ m}\Omega$ for Sample A, and $38.75 \text{ m}\Omega$ for Sample B. The small variation among these values indicates that the winding resistance was essentially maintained across the three conditions. Consequently, the observed differences in short-circuit current cannot reasonably be attributed to a substantial change in winding resistance within the measured data.

The BEMF increased from 4.73 V for Sample C to 4.99 V for Sample A, corresponding to an increase of approximately 5.50% . Sample B exhibited a BEMF of 4.82 V , which is approximately 1.90% higher than the untreated condition. The increase in BEMF is consistent with changes in the core's magnetic properties and indicates that the annealing treatment influenced the machine's electromagnetic characteristics.

3.5 Short-Circuit Current Behaviour

The short-circuit current represents one of the key electrical parameters investigated in this study. Sample C exhibited the highest measured short-circuit current of 52.36 A . Following annealing of Process A, the short-circuit current decreased to 48.15 A . This corresponds to a reduction of approximately 8.04% relative to the untreated condition.

Sample B also demonstrated a reduction in short-circuit current. The measured value was 49.85 A , corresponding to a reduction of approximately 4.79% relative to Sample C. Thus, both annealing treatments reduced the measured short-circuit current compared with the untreated core.

The reduction in short-circuit current is particularly significant when considered together with the measured inductance and resistance. The resistance remained almost constant, whereas the inductance increased following both annealing treatments. Therefore, the measured reduction in short-circuit current is consistent with a change in the machine's inductive impedance resulting from the modified magnetic condition of the core.

Among the investigated samples, Process A produced the highest inductance and the lowest short-circuit current. Process B also produced an increase in inductance and a corresponding reduction in short-circuit current, although the magnitude of the improvement was lower than that obtained with Process A.

The measured rate of change of current was $3.91 \text{ A}/50 \mu\text{s}$ for Sample C, $6.86 \text{ A}/50 \mu\text{s}$ for Sample A, and $5.49 \text{ A}/50 \mu\text{s}$ for Sample B. Sample A therefore exhibited the highest measured transient current rate. At the same time, Sample B showed an intermediate value. This parameter depends on the transient test conditions and the method used to extract the slope. Therefore, the present results are best interpreted as an experimental comparison between the three conditions rather than as an isolated material property.

3.6 Correlation between Magnetic and Electrical Behaviour

The results indicate a consistent relationship between the core's magnetic properties and the BLDC Motor's measured electrical characteristics. Both annealed samples showed higher permeability and lower H_{rms} than the untreated sample. This magnetic improvement was accompanied by an increase in line inductance and a reduction in short-circuit current.

For Sample A, the permeability increased by 48.25%, and the line inductance increased by 4.27%, while the short-circuit current decreased by 8.04%. Sample B exhibited a 46.54% increase in permeability and a 2.15% increase in line inductance, together with a 4.79% reduction in short-circuit current.

The results therefore suggest that the annealing treatment modifies the magnetic properties of the electrical steel core, which is reflected at the machine level through changes in inductance and short-circuit response. The effect is not accompanied by a significant change in winding resistance, strengthening the interpretation that the observed electrical differences are primarily associated with the magnetic treatment of the core.

The core-loss results provide an additional indication of the effectiveness of the annealing treatment. Both Process A and Process B reduced the measured core loss relative to the untreated condition. Process A achieved the larger reduction, while Process B produced a result that remained relatively close to Process A. When magnetic properties, core loss, and electrical characteristics are considered together, the results demonstrate that the thermal treatment influences everything from material magnetic behaviour to machine-level electrical performance.

4 Industrial Implications and Future Outlook

The results of this study demonstrate that the intended application and overall performance requirements should guide the selection of a heat-treatment process. Process A is better suited for high-efficiency applications, such as electric vehicle motors, renewable energy systems, and premium transformers, where superior magnetic properties can justify higher processing costs and deliver long-term energy savings. In contrast, Process B offers a more balanced solution with greater manufacturing consistency, lower production costs, and reliable performance, making it suitable for conventional industrial motors, consumer appliances, and other cost-sensitive products. From an industrial perspective, the choice should be based on the desired trade-off between efficiency, cost, and manufacturing robustness. Future research should focus on advanced microstructural characterisation, computational modelling, industrial-scale validation, and intelligent process-control strategies to further optimise electrical steel performance while ensuring cost-effective and sustainable manufacturing.

5 Conclusion

This study experimentally investigated the influence of two different annealing routes on the magnetic, core-loss, and electrical characteristics of electrical steel used in a BLDC Motor. Sample A was

processed using Process A, a multi-stage controlled annealing route, while Sample B was processed using Process B, a high-temperature rapid annealing route. Sample C was retained in the as-cut condition without heat treatment and was used as the untreated reference.

The magnetic measurements demonstrated a clear improvement after both annealing treatments. Relative to Sample C, Process A increased the measured B_{rms} by 2.44%, reduced H_{rms} by 35.83%, and increased permeability by 48.25%. Process B produced comparable changes, with a 2.20% increase in B_{rms} , a 34.73% reduction in H_{rms} , and a 46.54% increase in permeability.

The core-loss measurements further confirmed the effect of the annealing treatments. At 50 Hz and 1.5 T, the average core loss decreased from 5.90 W/kg for the untreated sample to 4.90 W/kg for Process A and 5.10 W/kg for Process B. These correspond to reductions of approximately 16.95% and 13.56%, respectively.

At the machine level, the line inductance increased from 104.90 μH for the untreated sample to 109.38 μH for Sample A and 107.15 μH for Sample B. Meanwhile, the winding resistance remained within a narrow range of 38.70–38.75 m Ω .

The short-circuit current decreased from 52.36 A for the untreated Sample C to 48.15 A for Sample A and 49.85 A for Sample B. Thus, Process A produced an 8.04% reduction. In contrast, Process B produced a 4.79% reduction relative to the untreated condition.

Based on the combined experimental results, Process A yielded the largest improvements in core loss, permeability, line inductance, and short-circuit current reduction among the investigated conditions. Process B, however, produced magnetic properties close to those of Process A.

The experimental results establish a clear link between annealing treatment, improved magnetic behaviour, increased machine inductance, reduced core loss, and reduced short-circuit current. The findings, therefore, provide a practical experimental basis for further optimisation of annealing conditions for BLDC Motor electrical steel cores.

Declarations

Funding Declaration

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Author Contribution

Vikas Patil - Concept / Original Paper Writing. Atul Jain - Prototype Testing & Validation Support / Review/ Validation. K.K.Gpta - Review / Guidance. V.P.P. conceptualised the study and wrote the main manuscript. V.P.P and A.J. performed prototype testing and validation. K.K.G. provided guidance and supervision for the research. A.J. and K.K.G. reviewed and validated the paper. All authors reviewed and approved the final manuscript.

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Data Availability

The experimental data generated and analyzed during this study, including inductance, short-circuit current, and related measurement data, are available from the corresponding author upon reasonable request.

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Figures

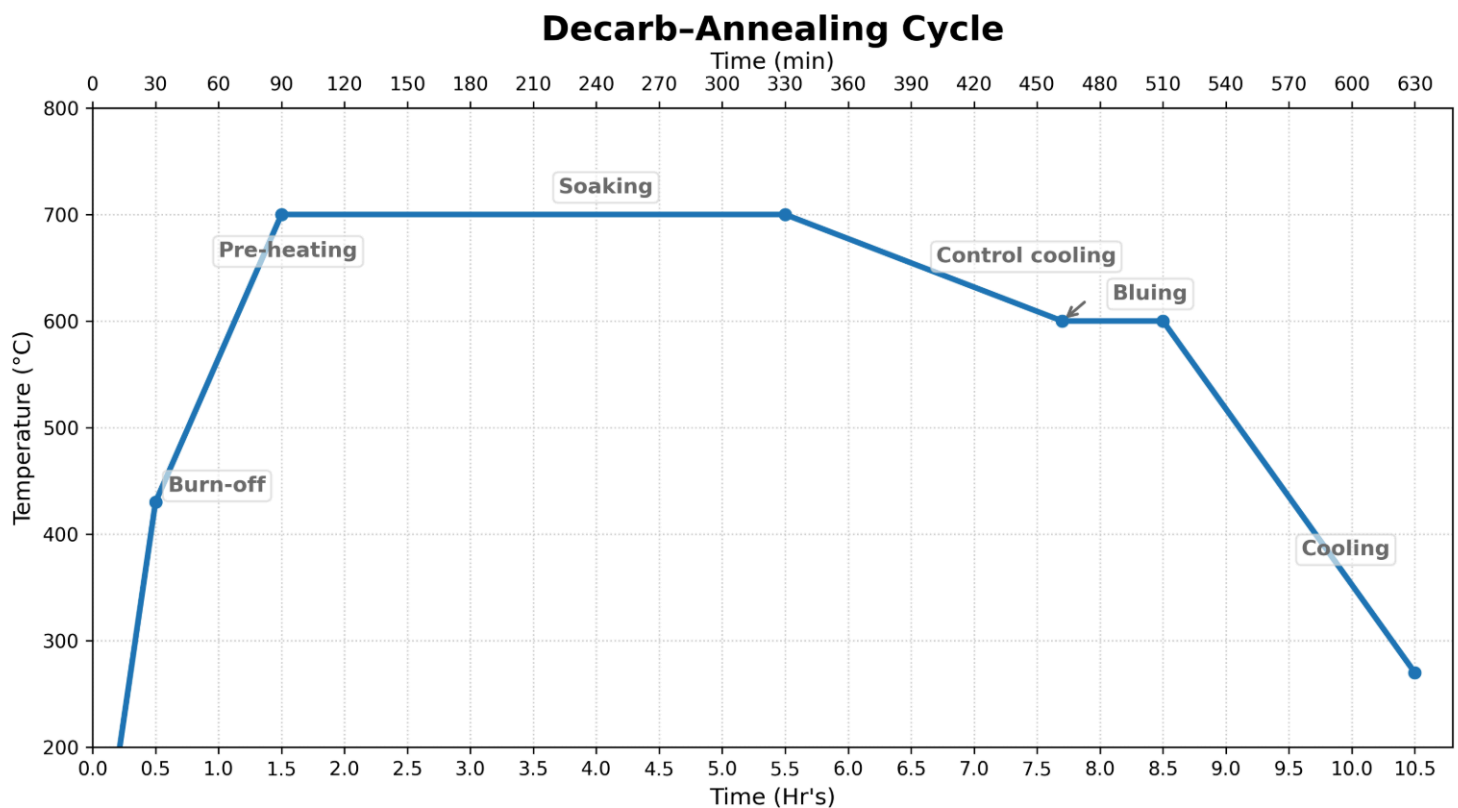


Figure 1

Fig.2. Temperature–time profile for Process A (Decarb–Annealing Cycle), highlighting staged burn-off, pre-heating, soaking, controlled cooling, bluing, and final cooling—total cycle time ≈ 9.5–10.5 h.

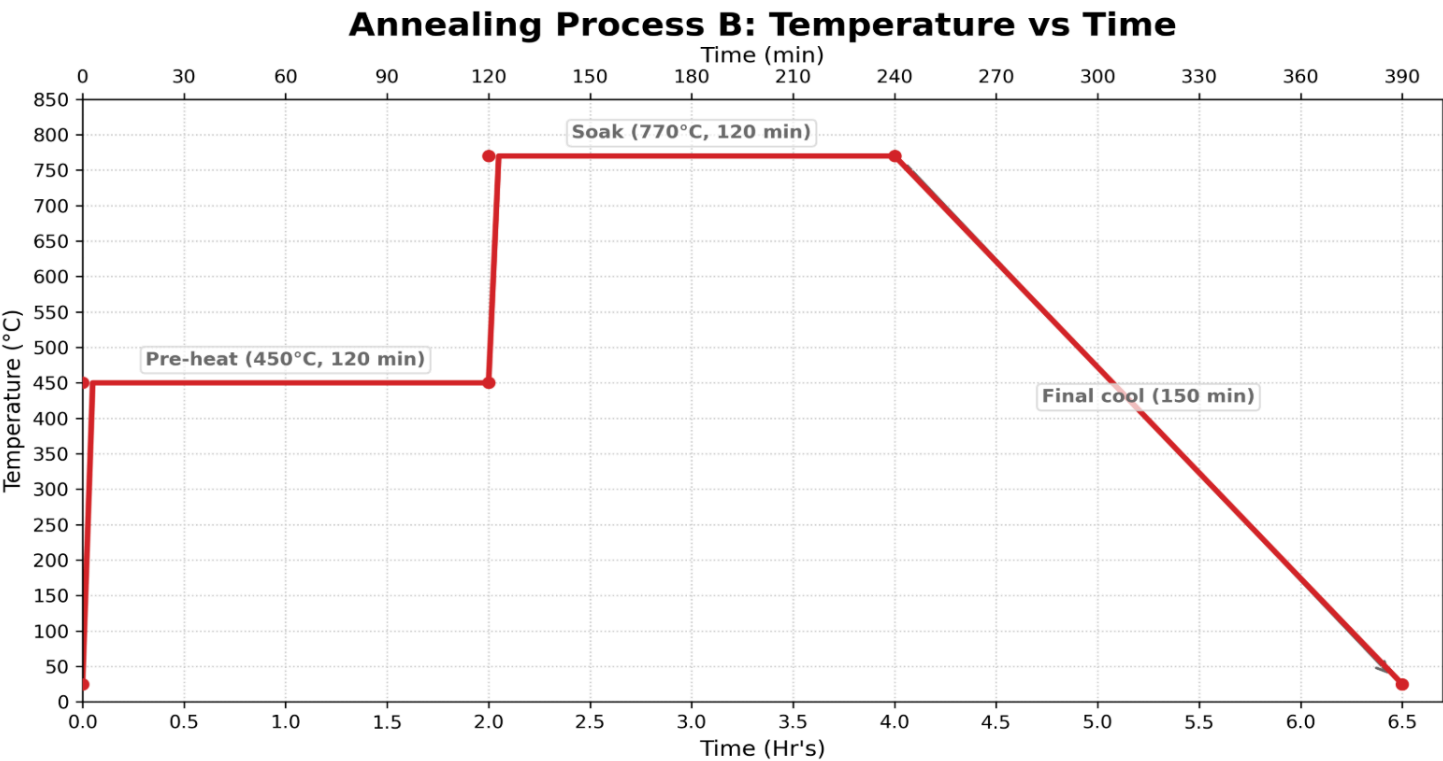


Figure 2

Fig.3. Temperature–time profile for Process B showing three stages: pre-heating, soaking, and controlled cooling.

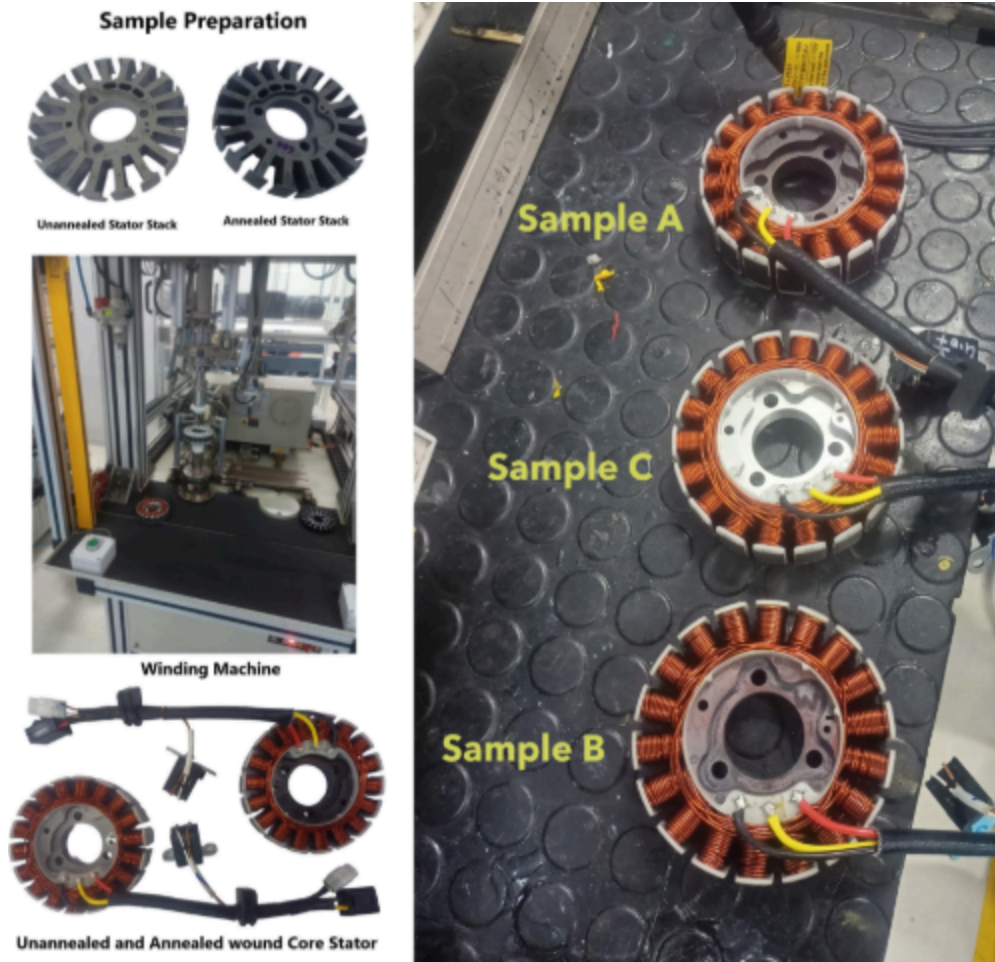


Figure 3

Fig.4. Representative specimens for each condition used in this study. Top: Process A (multi-stage controlled annealing); Middle: Control (no anneal, Sample C); Bottom: Process B (high-temperature rapid annealing).

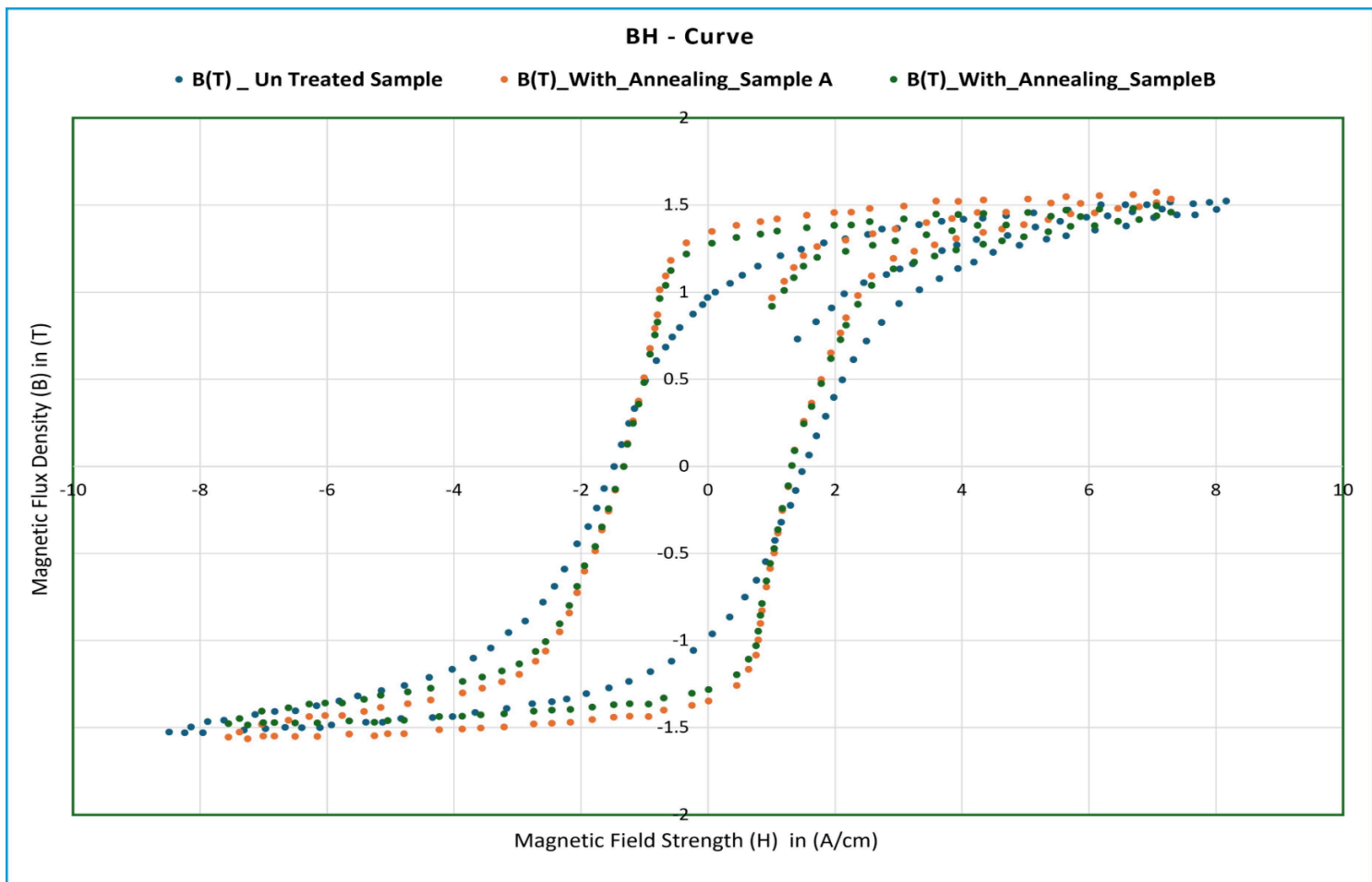


Figure 4

Fig.5. BH-curve of Samples A, B, and C, and the untreated one.



Figure 5

Fig. 6. Test Setup—Dynamometer and Measuring Instruments.

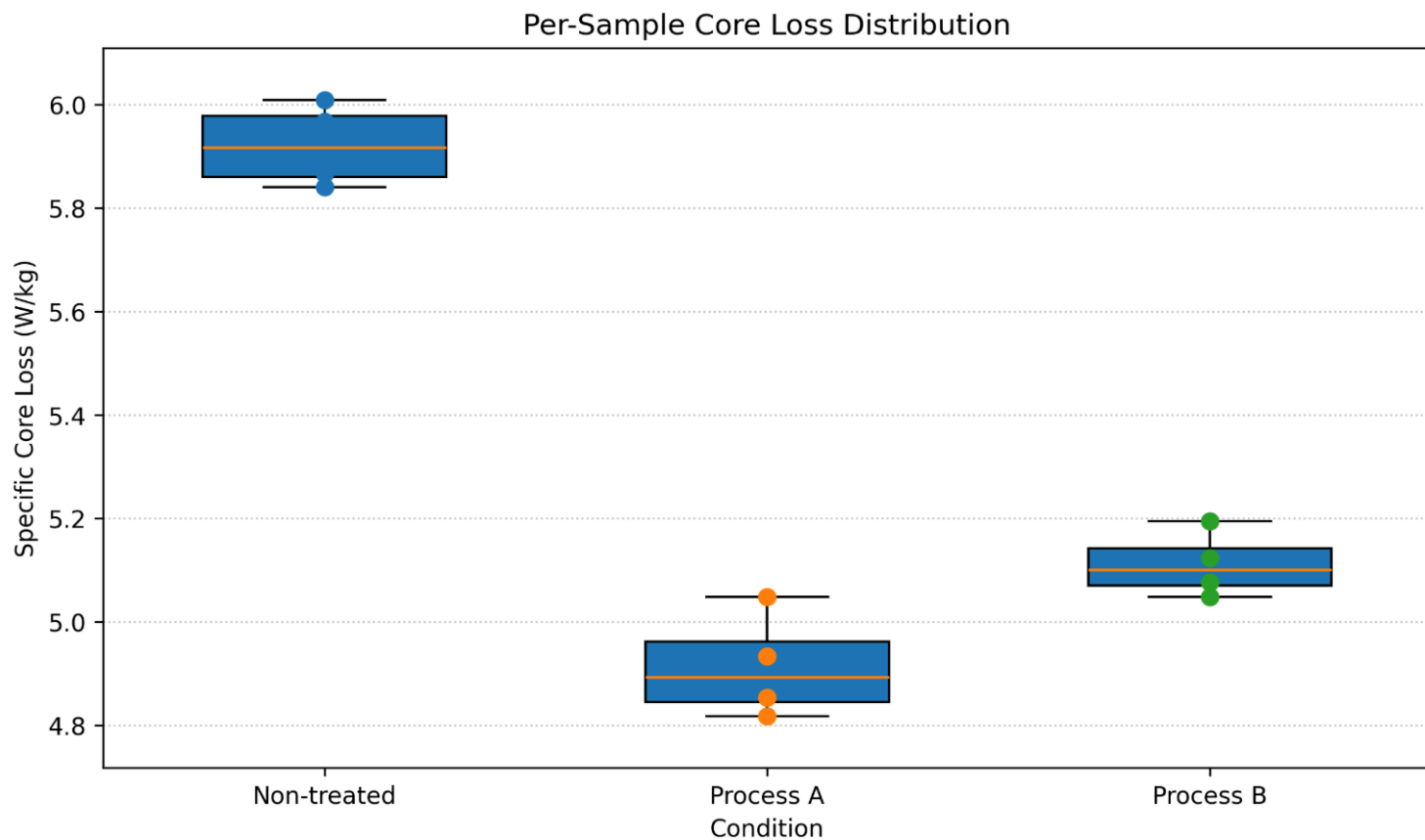


Figure 6

Fig. 7. Per-sample core loss distributions at 50 Hz and 1.5 T for non-annealed, Process A, and Process B conditions. The box shows the interquartile range with the median line; overlaid markers denote individual samples (n=4 per group).