TECHNotes

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Driving Efficiency through the Metallurgical Assessment of Stator Materials for EV Motors

Electric vehicles (EVs) are at the forefront of the automotive revolution, and at the heart of every EV motor lies a critical component: the stator. The materials used for stators play an integral role in maximizing efficiency, performance, and reliability. As EV technology evolves, the importance of selecting and optimizing stator materials becomes increasingly evident. Let's explore the metallurgical challenges and opportunities associated with stator materials, and how these innovations contribute to the energy-efficient future we're all working toward.

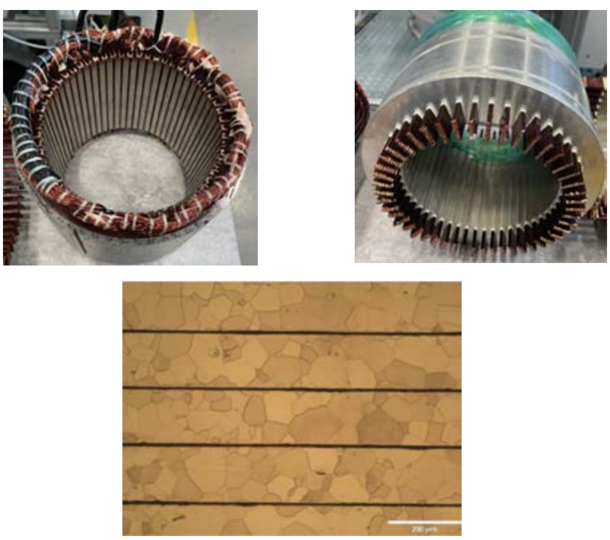


Figure 1. An EV stator and a typical microstructure of non-grain orientated electrical steel

Why Stator Materials Matter

The stator generates the rotating magnetic field that drives the rotor, making it a cornerstone of electric motor functionality. Its efficiency heavily relies on materials with exceptional magnetic properties, low core losses (eddy current and hysteresis), and thermal stability. Traditional laminated electrical steels, typically alloyed with silicon, dominate stator design due to their high magnetic permeability and low energy loss. However, the compact, high-power EV motors of today demand advanced materials that surpass traditional capabilities. These demands include:

- **High magnetic saturation flux density** to enhance power output.
- **Low core losses** to improve efficiency and range.
- **Thermal and mechanical stability** under high-speed operation.

Understanding the metallurgical properties and performance of stator materials is key to pushing EV efficiency and durability to new heights.

Material Considerations and Metallurgical Analysis

Electrical Steels and Alloys; Electrical steels, particularly non-oriented silicon steels (NGOES), are widely used for EV stators due to their isotropic magnetic properties. Advances in material science have yielded specialized steel grades with optimized compositions and grain structures to minimize core loss.

- High-Silicon Electrical Steels: Increasing silicon content reduces hysteresis losses, but it also introduces brittleness. Innovative processing methods, such as rapid cooling and stress-relief annealing, address this trade-off.
- Alloying Elements: Alloying elements like aluminium, phosphorus, and manganese refine the steel microstructure, and thus enhancing magnetic performance and mechanical strength.

Emerging Materials: Exploratory materials like amorphous metals and nanocrystalline alloys are being studied for their potential to revolutionize stator design.

- Amorphous Metals: With no crystal grain boundaries, these materials offer ultra-low core losses. Their unique structure eliminates many inefficiencies found in traditional electrical steels.
- Nanocrystalline Alloys: Ultra-fine grains provide superior magnetic softness and low energy dissipation, making them promising candidates for high-frequency, high-speed motors.

Magnetic Properties and Microstructural Optimization

The magnetic efficiency of stator materials hinges on their microstructure. Key properties like permeability, coercivity, and core loss are directly influenced by the grain size and boundary characteristics of the material.

- **Grain Size:** Larger grains reduce hysteresis losses but may compromise mechanical integrity. Precise heat treatment processes, such as annealing, balance this trade-off by refining grain structures. This offers improved strength, resistance to mechanical vibration and noise reduction
- **Stress Management:** Manufacturing processes like punching and rolling induce residual stresses, which degrade magnetic performance. Stress-relief annealing restores optimal properties, improving motor efficiency.

Advanced modelling tools now simulate the effects of stress and strain during processing, helping engineers refine designs and processes to minimize performance degradation.

Powder Metallurgy and Emerging Alternatives

Powder metallurgy (PM) is revolutionizing stator manufacturing by enabling the production of soft magnetic composites (SMCs). These composites offer three-dimensional magnetic flux paths, reduced core losses, and improved integration capabilities for compact motor designs. Advantages of PM materials include:

- Complex Geometries: SMCs can be molded into intricate shapes, allowing for better space utilization in EV motors.
- High-Frequency Performance: Ideal for modern high-speed motors, SMCs excel at minimizing energy loss at elevated frequencies.
- Integration: PM enables the creation of multi-functional parts, reducing assembly complexity and weight.

Innovations in binding agents, compaction techniques, and alloy compositions are pushing PM materials toward even greater performance. Nanocrystalline PM materials are particularly exciting, offering superior magnetic properties and thermal stability.

Thermal Considerations

EV motors operate under intense thermal conditions, with rapid cycling and high rotational speeds generating substantial heat. Stator materials must effectively manage this heat to ensure consistent performance and long-term durability. Use of high silicon steels resist thermal fatigue while maintaining magnetic properties at elevated tempers. Other alloys, such as cobalt-iron alloys offer higher thermal conductivity, dissipating heat more effectively but do come at a cost. Other innovative solutions from a materials engineering is utilisation of thermal interface materials that improve heat transfer between components of a stator.

Alternative manufacturing techniques, such as laser cutting, reduce residual stresses that impede thermal conductivity, further enhancing temperature management.

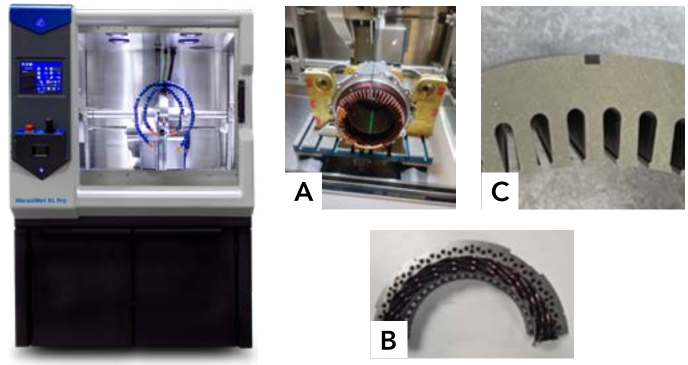
Balancing Magnetic and Mechanical Properties

Stator materials must not only perform magnetically but also endure the mechanical stresses of high-speed operation. This balance is achieved through precise metallurgical control of mechanical strength; this is achieved through alloying additions and grain refinement heat treatment processes to improve yield strength and fatigue resistance. Additional techniques such as nanoprecipitation serve to strengthen the materials without compromising magnetic performance.

Metallography: Decoding the Material DNA

Metallographic analysis reveals the microstructural secrets of stator materials, offering insights that drive innovation and performance improvements. The process involves sectioning on an abrasive cutter, to extract sample specimens. These undergo a sequence of processes involving mounting, grinding and polishing to ensure deformations free surface is achieved before any analysis is carried out. Metallurgical procedures include:

- **Sectioning:** A stator is sectioned on a large cutter to extract sample specimens of various components. This is achieved on abrasive cutter such as AbrasiMet® XL Pro. Key challenges involve selection of right abrasive blade and proper stator clamping for efficient sectioning.



AbrasiMet XL Pro

Figure 2. (a) A stator with its housing undergoing metallographic sectioning, (b) and (c) Extracted specimens

- **Mounting:** The extracted specimens are mounted using either cold mounting (use of epoxies or acrylic resins) or hot mounting (using SimpliMet® 4000 and appropriate resin) processes. The process allows easy semi-automatic preparation of mounted samples in a grinder polisher, AutoMet 300. Embedding samples provides mechanical support to prevent steel laminates coming apart during grinding and polishing procedures.

SimpliMet 4000

Figure 3. Mounting techniques employed

- **Grinding and Polishing:** The mounted samples are taken through grinding steps using progressively finer abrasives to remove damage from sectioning, and then through polishing stages to provide a deformation free surface ideal for microstructural evaluation.

AutoMet® 300

Surface	Abrasive / Size	Load - lbs [N] / Specimen	Base Speed [rpm]	Relative Rotation	Time [min:sec]
CarbiMet	320grit [P400] SiC water cooled	6 [27]	300		Until Plane
UltraPad	9µm MetaDi Supreme Diamond*	6 [27]	150		5:00
VerduTex	3µm MetaDi Supreme Diamond*	6 [27]	150		3:00
MicroCloth	0.05µm MasterPrep Alumina	6 [27]	150		2:00

= Platen   = Specimen Holder   *Plus MetaDi Fluid Extender as desired

Figure 3. An AutoMet 300 and a preparation route for ferrous materials

Key techniques for analysis:

1. Optical Microscopy: Identifies grain size, distribution, and defects in the microstructure.

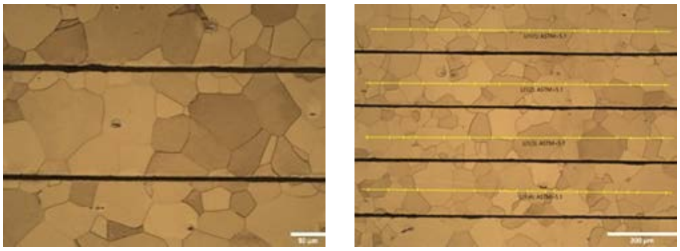
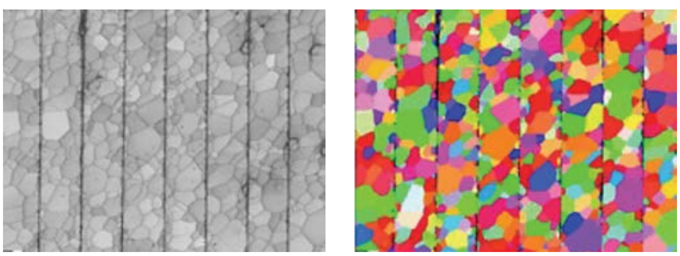


Figure 5*. Optical micrograph as etched non grain orientated electrical steel, lines between are binder material. Grain size with ASTM no. 5.1 ≈ 55µm*

2. Scanning Electron Microscope (SEM) and Electron Backscatter Diffraction (EBSD): SEM further examines grain boundaries and surface irregularities and an overview of alloying element distribution within the alloy. EBSD on the other hand analyses crystallographic goss texture, which directly impacts magnetic efficiency. Analysis shows grain structure that is uniform with fairly equiaxed grains indicating a well-recrystallised structure. The consistency in microstructure is indicative of a controlled process of creating electrical steel sheet laminates.

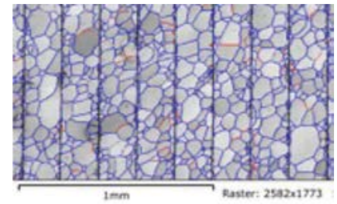


Band contrast image – consistent microstructure

IPF map showing grain crystallographic orientations

Figure 6*. SEM/EBSD micrographs of a NGOES samples.*

Textural characterisation aims to identify preferred crystallographic orientations of the grains in the material offering insights into materials anisotropic properties, grain orientation distributions offers ways to predict material performance under stress, shows prior deformation processes such as rolling or forging, and also allows us to understand heat treatment effects by assessing recrystallisation, grain growth or any phase transformations.



Show grain boundary assessment (low and high angle boundaries)

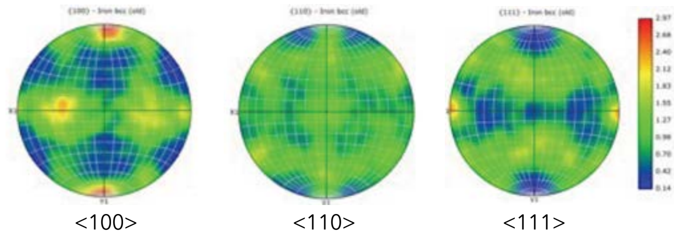


Figure 7*. SEM/EBSD micrographs of a NGOES samples.*

3. Other techniques:
   - X-Ray Diffraction (XRD) can also be used to evaluate phase distributions and magnetic properties.
   - Non-destructive evaluation (NDE) techniques, such as magnetic flux leakage and ultrasonic testing, complement metallography by detecting internal defects in stator components.

Future Innovations in Stator Materials

The next generation of stator materials promises groundbreaking advancements in performance, efficiency, and sustainability.

- Nanostructured Alloys: Combine lightweight design with superior magnetic properties, ideal for compact EV motors.
- Additive Manufacturing: Enables intricate, customized stator geometries for optimal performance.
- Composites: Hybrid materials reduce weight while enhancing efficiency.

AI-driven materials research is accelerating alloy development, allowing engineers to predict outcomes of new compositions and processes, saving time and resources.

Driving the Electric Revolution Together

The stator is not just a component - it's the linchpin of EV motor performance. From its microstructure to its thermal management, every aspect of the stator contributes to the efficiency and sustainability of electric vehicles.

Collaborative innovation between materials scientists, engineers, and manufacturers is key to overcoming challenges and unlocking the potential of next-generation stator materials.

Are you working on new materials or methods for EV stators? Share your insights, challenges, and breakthroughs. Let's work together to drive the electric revolution forward.

#ElectricVehicles #MaterialsScience #StatorMaterials #Metallurgy #MicrostructureAnalysis #Sustainability #EngineeringInnovation #EVTechnology #HeatTreatment

BUEHLER

BUEHLER Worldwide Headquarters
North America-South America Offices
41 Waukegan Road
Lake Bluff, Illinois 60044-1699 USA
P: 800 BUEHLER (800-283-4537)
P: (847) 295-6500
www.buehler.com | info@buehler.com

European Headquarters
BUEHLER Germany
info.eu@buehler.com

BUEHLER France
info.eu@buehler.com

BUEHLER United Kingdom
info.eu@buehler.com

BUEHLER China
info.cn@buehler.com

BUEHLER Japan
info.japan@buehler.com

BUEHLER Asia-Pacific
info.asia@buehler.com

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