TECHNotes

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Metallurgical Assessment of Stator Windings in Electric Motors

Electric motors are at the heart of modern vehicles, with **stator windings** playing a crucial role in converting electrical energy into motion. As the demand for high-performance motors increases, optimizing stator windings through advanced materials and metallurgical techniques is essential. This article explores key aspects of stator winding construction, material selection, and metallographic assessment to enhance performance and reliability.

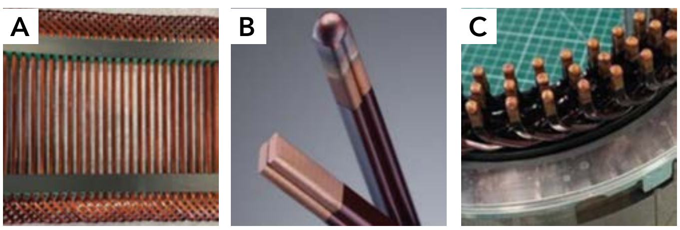


Figure 1. (a) Stator rectangular winding layout, (b) Hairpin joint, (c) Hairpin welds on rectangular lap winding

From Wires to Hairpins: The Evolution of Stator Windings

It wasn't long ago that **round-wire concentric windings** ruled the motor world. Simple, effective, and easy to manufacture, these windings delivered consistent results for decades. However, the rise of compact, high-power motors in EVs demanded more: higher slot-fill factors, better thermal management, and reduced copper losses.

Enter the age of **rectangular /hairpin** and **formed Litz wire windings**, these technologies allow one:

- To maximize **slot-fill factors** (80% in rectangular windings vs. 65% in round wires), allowing greater copper density.
- To considerably improve **thermal management** by reducing hot spots and enhancing heat dissipation.
- Reduce **copper losses**, which is critical for achieving high efficiency in compact motors.

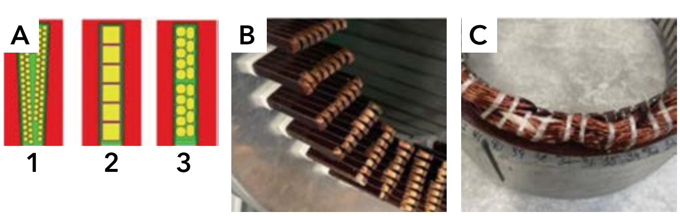


Figure 2. (a) [1] Round Wire [2] Rectangular Litz wire [3] Formed Litz wire, (b) Rectangular lap winding, (c) Traditional round wire winding

This shift not only transformed the geometry of stator windings but also introduced new challenges in **material selection, joining techniques,** and **quality control.**

Material selection matters: Copper, Aluminium, and Coatings

- **Copper (Cu)** is the gold standard for electrical conductivity and preferred material for stator windings, however, its cost and weight post significant challenges in optimisation processes.
- **Aluminium (Al)** offers a lightweight alternative to copper, the main challenge is the requirement for advanced joining techniques laser beam welding of hairpin welds.
- Insulation **coatings** offer reliability of stator windings in EV motors. Coatings such as such as polyimide and epoxy, protect windings from thermal degradation and electrical failure.
- Innovations in **dielectric materials** ensure higher thermal conductivities while maintaining robust insulation, making them critical for managing the increasing voltage demands of EV motors.

The Role of Metallographic Analysis in Stator Windings

Metallographic analysis provides a window into the key features of stator windings. By examining the microstructure, manufacturing defects and material integrity, metallurgists can:

- Evaluate **performance** by identifying features like grain size, phase distributions, and defects that influence electrical conductivity and mechanical reliability.
- Monitor manufacturing **quality** by detecting defects such as voids, pores, cracks, incomplete welds in windings.
- **Optimise** material by analysing how different alloys, coatings or alternative materials perform under thermal and mechanical stresses.

Key Focus Areas in Metallographic Assessment of windings

1. **Microstructural Analysis:**
    - Understanding grain size and textural effects of copper and/or aluminium windings is key, e.g. high-speed motors benefit from coarse grains for enhanced conductivity, reduced eddy currents and resistive loses. Whereas high stress applications require fine grains in to cope with high mechanical loads or vibrations.
    - Grain size engineering through cold work followed by annealing, adjustment of alloy elements and recrystallization control.
2. **Weld quality:**
    - Assessing welds at hairpin connections or lap winding joints for porosity, incomplete fusion, or cracks e.g. Laser-welded hairpins are prone to **pores** and **keyholes**, which can compromise joint strength.
    - Correlating weld quality to electrical resistance and mechanical robustness. High-speed X-ray imaging and acoustic monitoring can detect these defects in real time.

3. **Coating Integrity:**
    - Evaluating the thickness, uniformity, and adhesion of polyimide or epoxy coatings has a bearing on their ability to withstand high thermal and electrical stresses in modern motors.
    - Identifying degradation due to thermal or chemical exposure.
4. **Defect Detection – non-destructive:**
    - Pinpointing voids, pores, or inclusions that can compromise electrical and mechanical performance, e.g. use of non-destructive techniques like **X-ray computed tomography (XCT)** to reveal internal defects, such as pores and cracks, without damaging the sample.

The Art of Metallographic Preparation – Case: Assessing hair pin weld quality.

1. Sectioning: Samples are sectioned using precision saws, such as the IsoMet® High Speed, to extract hairpin welds or rectangular winding cross-sections as the regions of interest. Precision sectioning is preferred as it results in specimens with the least amount of residual damage.

IsoMet® High Speed

Parameters:
Blade: 15HC or 104061010
Blade Speed: 2500rpm
Feed Rate: 7mm/min.
Smart-Cut: On

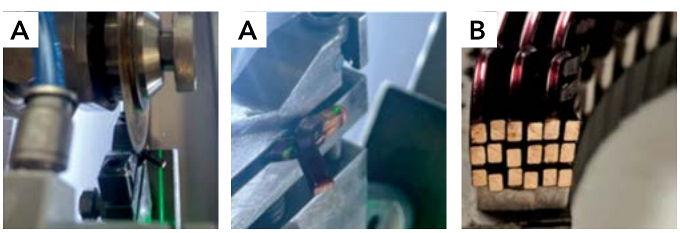


Figure 3. (a) Cross-section through the hairpin weld (b) Windings wire cross-section

2. Mounting: After sectioning, the samples are mounted using cold mounting resins, epoxy (EpoxiCure® 2) or acrylic (Varidur® 200), for ease of handing and semi-automatic preparation during grinding stages.

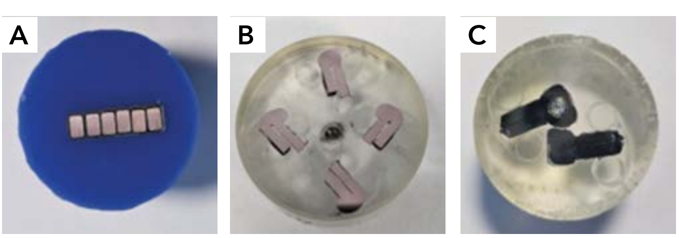
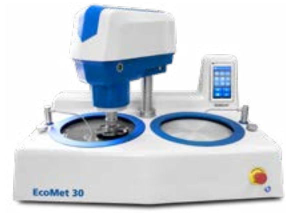


Figure 4. (a) Stator alot winding cross-section, (b) Copper hairpin welds ~ EpoxiCure®, (c) Aluminium hairpin welds ~ EpoxiCure® 2

3. Grinding & Polishing: This is normally done on either an AutoMet® 250/300 or EcoMet® 30 grinder polisher, ensuring correct procedure is followed for the material type (Cu, Al, coatings) being prepared. After the final step, the sample is ready for etching to reveal microstructural details.

Electrolytic polishing can be used for copper or aluminium samples to enhance surface quality and reveal microstructure more clearly when carrying out high end electron microscopy.



EcoMet® 30 Semi Automatic grinder-polisher

4. Etching: Selective chemical etching highlights microstructural features like grain size and phase distribution. Examples of etchants to use include ammonium persulfate, Marbles, or Ferric chloride for copper microstructures. For aluminium microstructures, electrolytic anodisation using bakers reagent works well for the structure and crystallographic orientation information. Be cautions not to overdo it as overexposure does result in damage of fine microstructural features.

Step No.	Surface	Abrasive / Size	Force / specimen	Time (min:sec)	Base Speed (rpm)	Rotation
1	SiC paper	P400 water cooled	20N	Until Plane	200	
2	SiC paper	P1200 water cooled	20N	01:00	200	
3	PoliCloth	3um Diamond Metadi Supreme	25N	05:00	150	
4	Trident	1um Diamond Metadi Supreme	25N	03:00	150	
5	ChemoMet	0.02-0.06um MasterMet	20N	02:30	150	

– Platen – Specimen Holde

Figure 5. Typical preparation routine for copper samples

5. Imaging and Analysis:

- **Optical Microscopy:** Ideal for inspecting grain structure, phase distribution, and surface defects in copper or aluminium windings. Also allows coating thickness measurements and visual documentation of defects like cracks or voids.

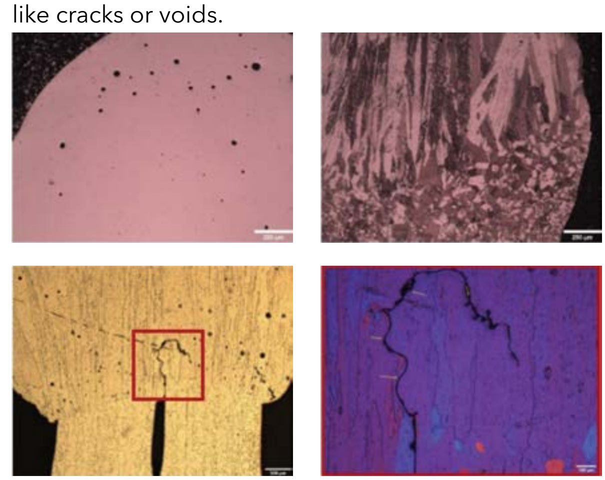


Figure 6. (a) As polished Cu hairpin weld with voids, (b) Etched micro-structure at weld base material, (c) Al hairpin weld - etched, (d) Crack in the hairpin wled on Aluminium hairpin

- **Hardness Testing:** Microhardness testing is used to evaluate mechanical properties of the copper or aluminium at different zones, such as the weld nugget or heat-affected zone (HAZ) enabling full microstructural characterisation. Excessively harder regions are not desirable.

Wilson® VH3300 All in One Hardness Tester

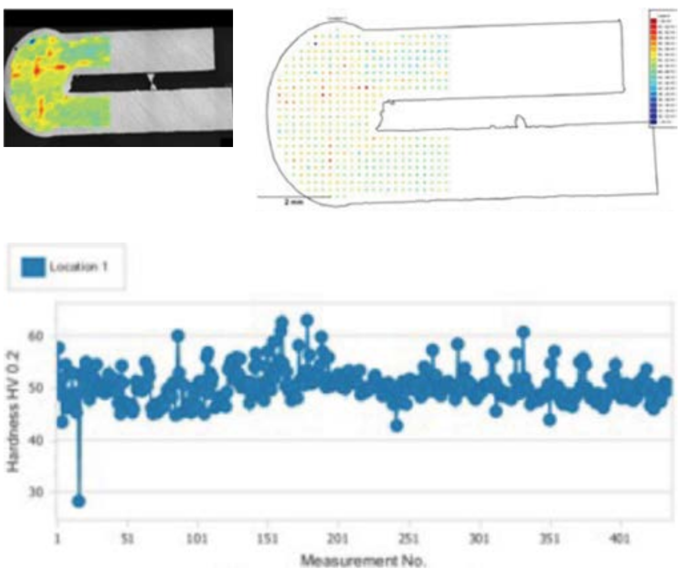


Figure 7. (a) Hardness maps around Cu hairpin weld, hot heatmap areas are indicative of higher hardness values, (b) Quantitative data plot

- **Scanning Electron Microscopy (SEM):** Provides high-resolution imaging of grain boundaries, inclusions, and weld interfaces. When equipped with Energy Dispersive X-ray Spectroscopy (EDS) elemental composition can be discerned easily, ensuring proper alloying and coating integrity.
- **Electron Backscatter Diffraction (EBSD):** Maps the crystallographic orientation of grains in copper windings and can be adopted when studying recrystallization patterns and their impact on electrical conductivity. - Recrystallization texture attributed to welding parameters.

Driving Innovation Through Metallography

Metallographic analysis isn't just about finding flaws - it's about pushing the boundaries of what's possible:

- **Better Welds:** Understanding the microstructure of laser-welded hairpins leads to stronger, more reliable connections.
- **Thermal Optimization:** Tailoring grain structures reduces hot spots, extending motor lifespan.
- **Scalable Manufacturing:** Insights from metallography ensure quality control for mass production.

Conclusion: Shaping the Future of Electric Mobility

As EV adoption accelerates, the demands on electric motors will only grow. **Metallography and materials science** are the twin pillars that will support this evolution, ensuring motors are not just powerful, but also efficient, reliable, and sustainable.

Have you worked on stator windings or their metallographic analysis? Share your experiences and insights.

For further queries please contact us on lab.eu@buehler.com lab.us@buehler.com or our website at www.buehler.com and for solutions applicable to automotive industry.

Let's collaborate - one microstructure at a time.

#Metallography #ElectricVehicles #MaterialsScience #StatorWindings #EngineeringInnovation #QualityControl

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