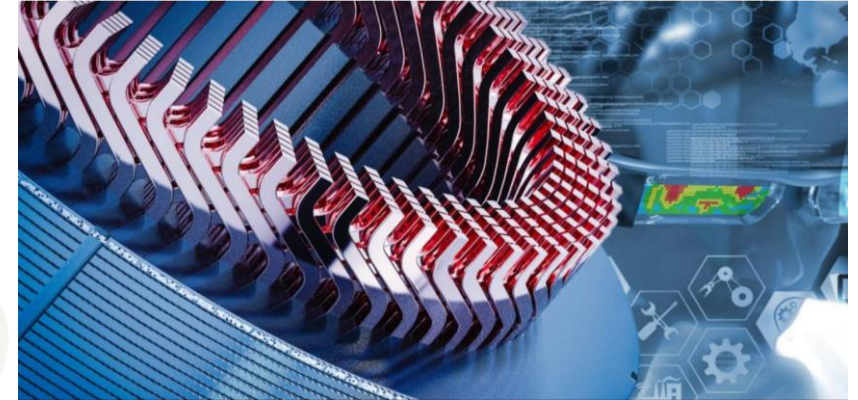


EV / HEV MANUFACTURING · ELECTRIC DRIVE PRODUCTION

Electric Motor Manufacturing

Key concepts of stator (hairpin) and rotor production for automotive traction drives

Adapted from the guides by **PEM RWTH Aachen University & VDMA** (2020 · 2022)



Bachelor in Sustainable Transport

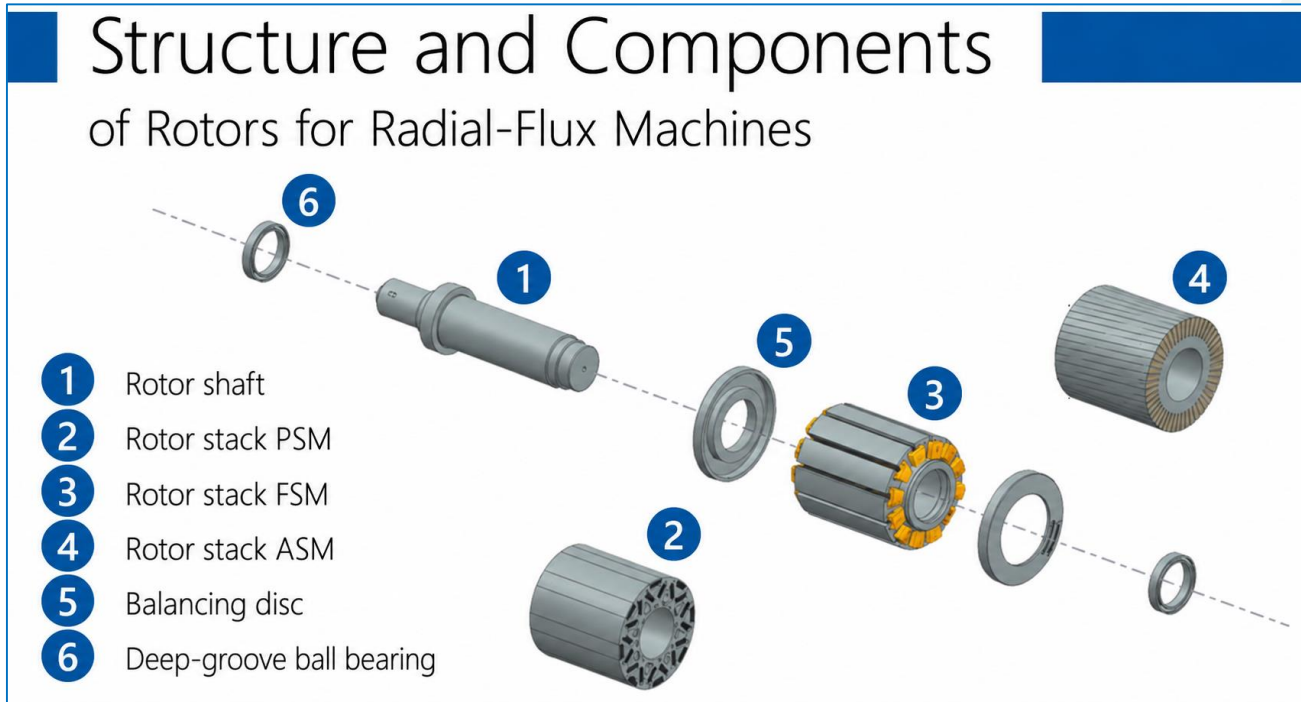
"Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them."

Sustainable Transportation within the Framework of Green Deal - SPHERE

Call: ERASMUS-EDU-2023-CBHE-STRAND-2

Project Number: 101128065

Stator and rotor: the two core assemblies



Exploded view of a rotor for radial-flux machines (1 shaft, 2 PSM core, 3 ESM core, 4 ASM core, 5 balancing disc, 6 bearing)

Key concepts

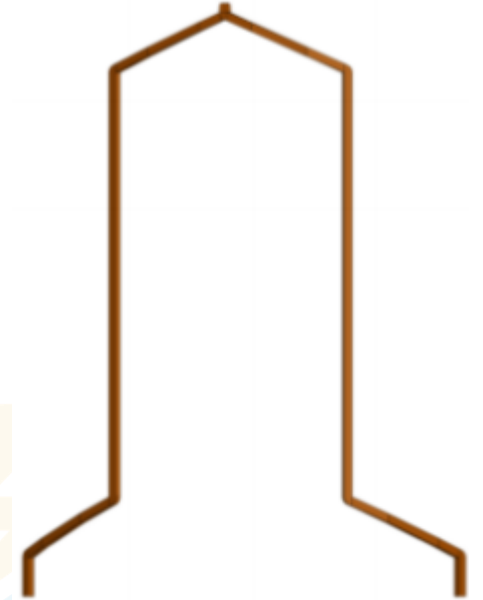
- An electric motor pairs a stationary stator with a rotating rotor; the stator's three-phase windings build a rotating magnetic field.
- The rotor follows that field: synchronous machines (PSM, ESM) lock to it, asynchronous machines (ASM) lag behind it.
- Stator manufacturing is dominated by hairpin winding for traction drives; rotor manufacturing differs by topology (PSM / ESM / ASM).
- This deck covers the full production chain of both assemblies — from raw conductor and shaft to the tested, balanced component.



Hairpin winding technology

From wire winding to pre-formed hairpins

- Hairpins are U-shaped, rectangular (flat) copper bars inserted into the slots of the laminated sheet-metal package — a forming-based assembly process.
- They replace classic needle, flyer and pull-in winding; the laminated package is built from insulated electrical sheets 0.1–1.0 mm thick.
- Already used in generators, with a strong trend toward automotive traction motors (synchronous and asynchronous, distributed winding).



Front view of a hairpin

Advantages

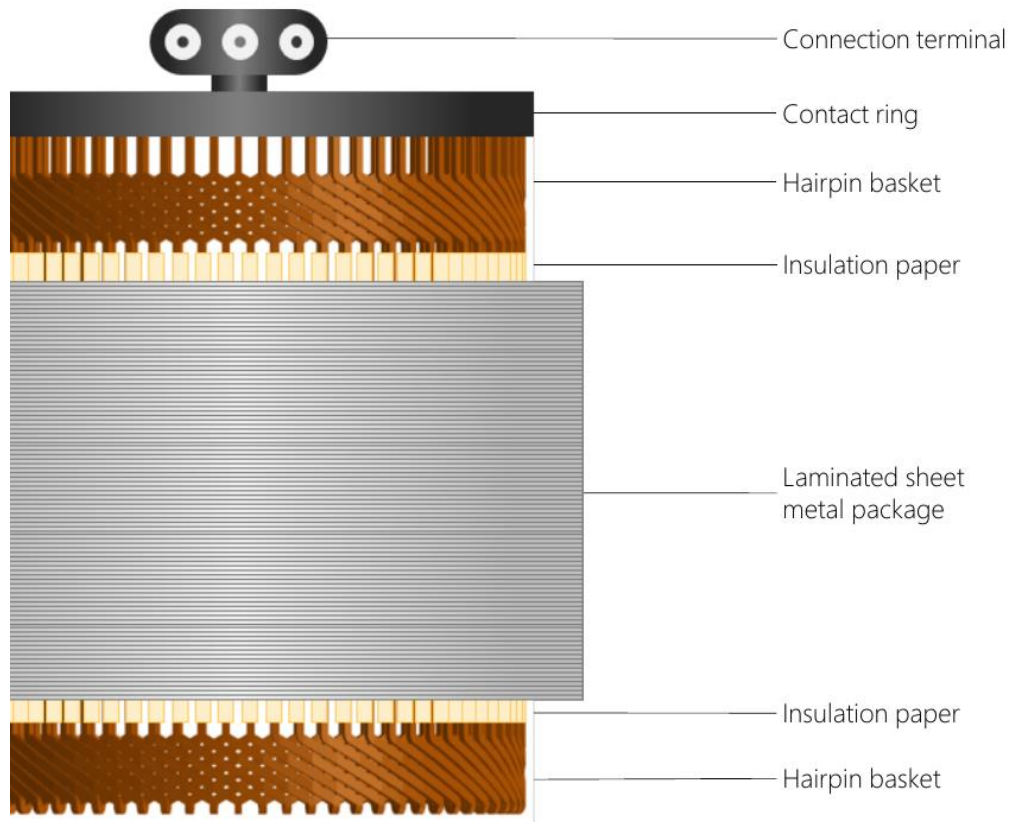
- Very high slot fill factor (~73 %) vs. 45–50 % for round-wire stators.
- Large conductor cross-section → high currents and high-torque motors.
- Deterministic, automatable assembly → series production and scalability.

Trade-offs

- Skin effect must be considered at high frequency; limited flexibility.
- Cost efficiency reached at roughly 200,000 units per year.
- Many hairpin types per stator (approx. 3–16) require sorting and handling.

Structure and components of the hairpin stator

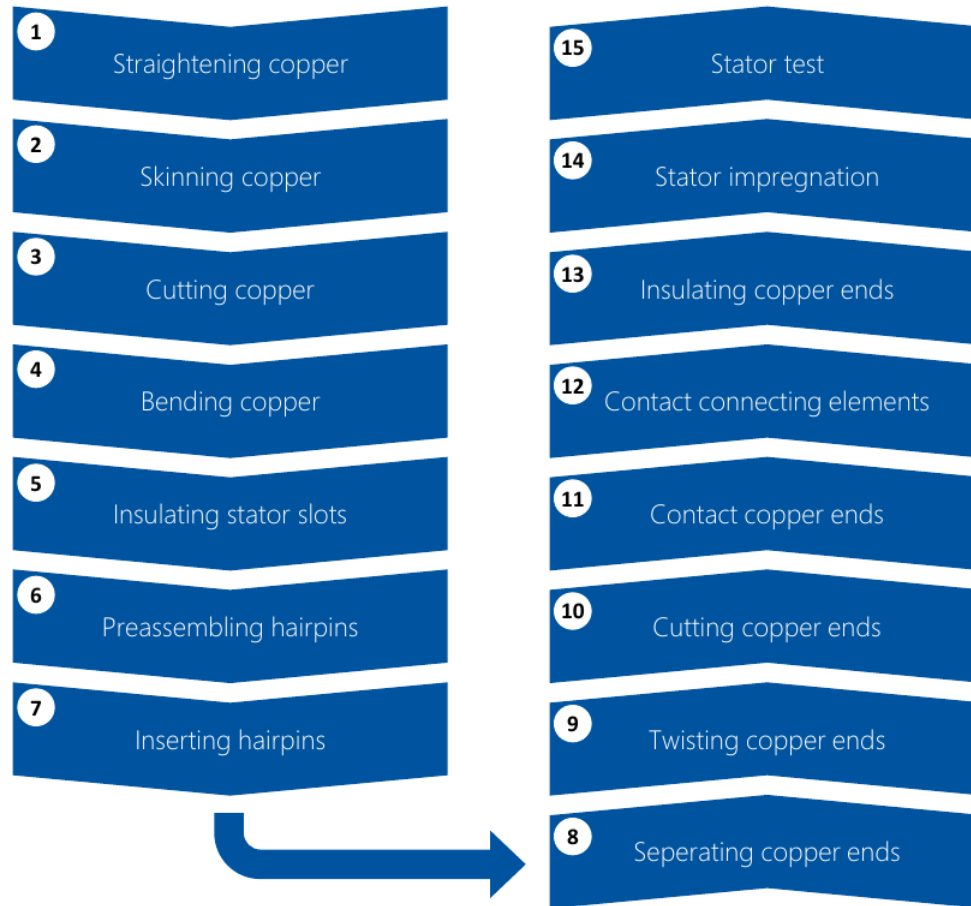
Structure and components of the hairpin stator



Components

- Connection terminal — interface to the power electronics.
- Contact ring with jumpers / star connectors — links non-adjacent copper ends per the winding scheme.
- Hairpin basket — the pre-assembled set of U-shaped conductors forming the winding head.
- Insulation paper — separates conductors from the grounded laminated package.
- Laminated sheet-metal package — stacked insulated electrical sheets carrying the magnetic flux.

The 15-step hairpin stator process chain

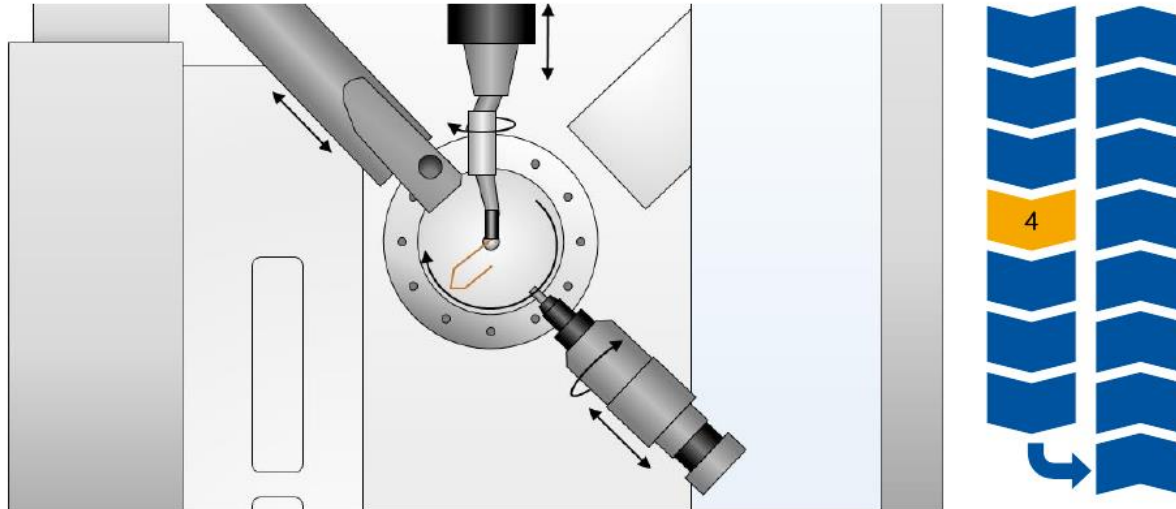


Reading the chain

- Steps 1–4 prepare the conductor: straighten, skin (strip), cut and bend the copper.
- Steps 5–9 form the winding: insulate slots, pre-assemble and insert hairpins, separate and twist the copper ends.
- Steps 10–12 contact the ends: cut to height, laser-weld and add connecting elements.
- Steps 13–15 finish the stator: insulate the welded ends, impregnate and test.

Conductor preparation (steps 1–4)

2D and 3D bending (CNC bending)



CNC bending of the copper wire (step 4)

The four steps

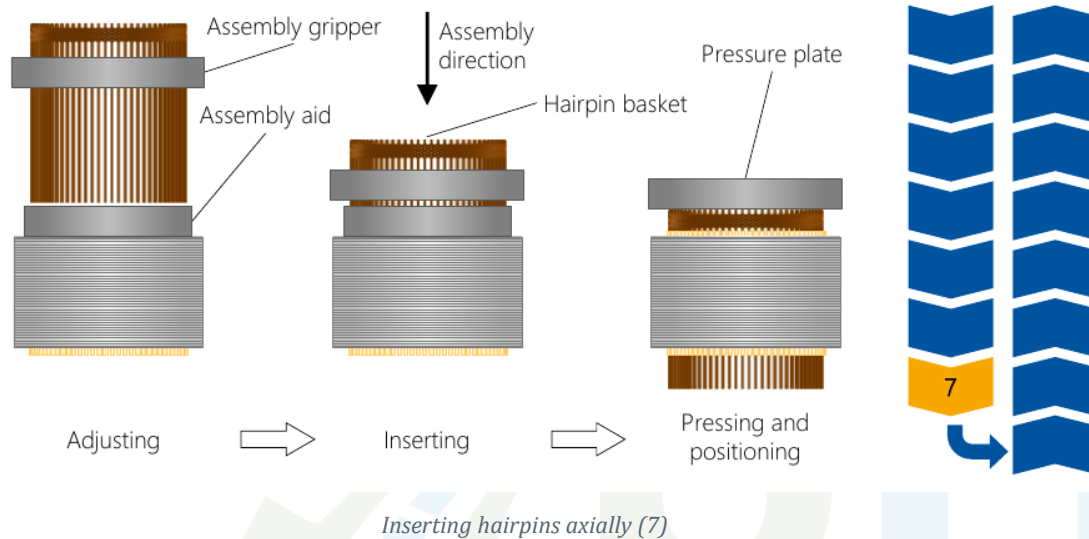
- Straightening: multi-stage rollers remove coil curvature from the flat wire.
- Skinning: lasers selectively strip the insulation at the wire ends.
- Cutting: shear-cutting to length without burrs or cross-section deformation.
- Bending: 2D and 3D (CNC) shaping so the legs reach different stator layers.

Quality focus

- Low residual curvature, helicity and wire damage after straightening; clean, residue-free stripped zones.
- Form, angle and position tolerances held through bending; spring-back compensated, no insulation damage on the outer radius.

Forming the winding (steps 5–9)

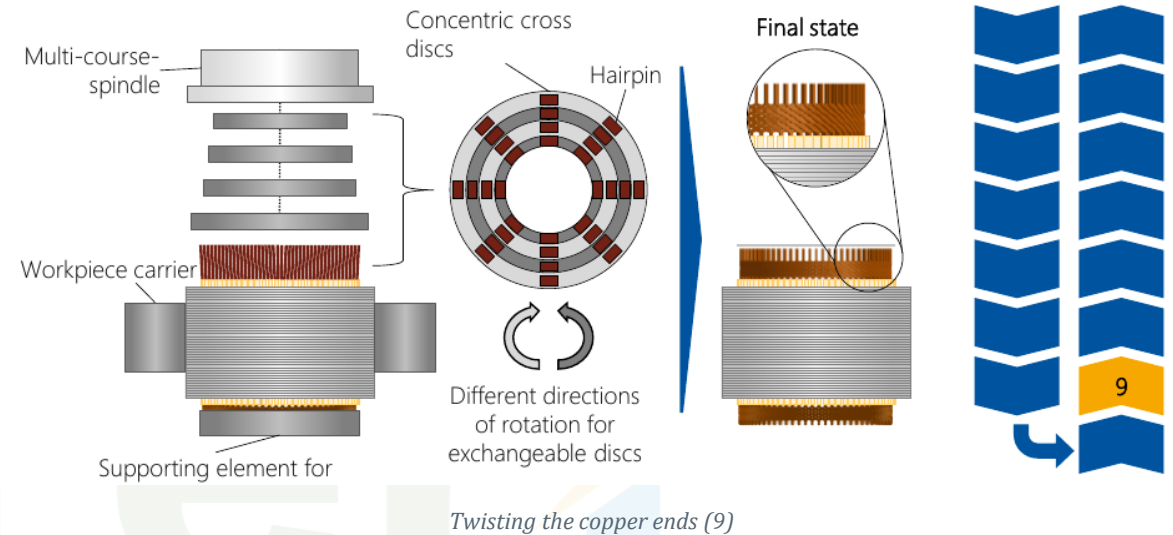
Insert hairpins axially in the laminated sheet metal package



Insert & pre-assemble

- Slots are insulated with folded paper; hairpins are pre-assembled into a basket and inserted axially (joining gap < 0.1 mm).
- A pressure plate aligns the conductors to their final axial position.

Transverse arrangement according to the winding scheme

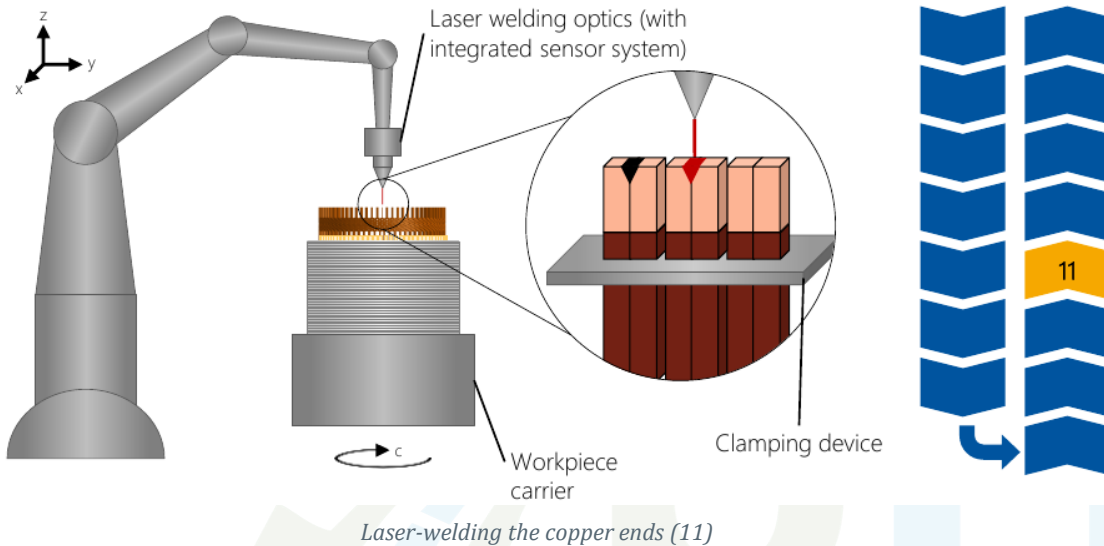


Separate & twist

- Copper ends are radially separated for tool access, then twisted into an S-shape so they sit parallel per the winding scheme.
- Free wire ends are supported in the bending radius to avoid damage.

Contacting and finishing (steps 11–15)

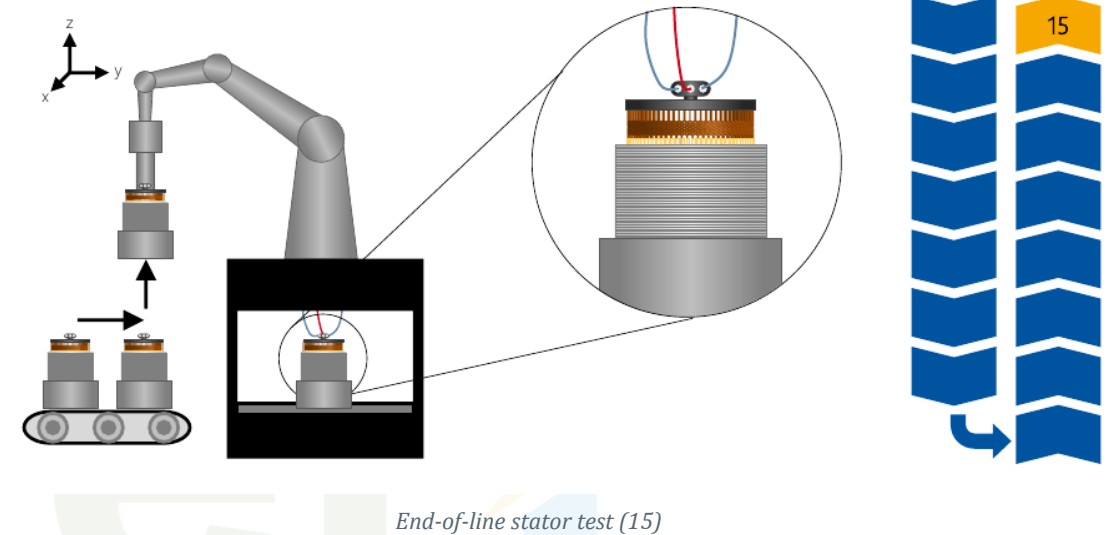
according to the specified winding scheme



Contacting & welding

- Adjacent copper ends are clamped and laser-welded per the winding scheme; a camera sensor positions the ends.
- Connecting elements (contact ring, jumpers, star connectors) link non-adjacent ends.

Stator test at the end of stator production



Insulate, impregnate & test

- Welded ends are re-insulated (whirl sintering) against short circuits; the stator is impregnated (resin) for strength and heat transfer.
- Final test: insulation strength, partial discharge, resistance and winding scheme.

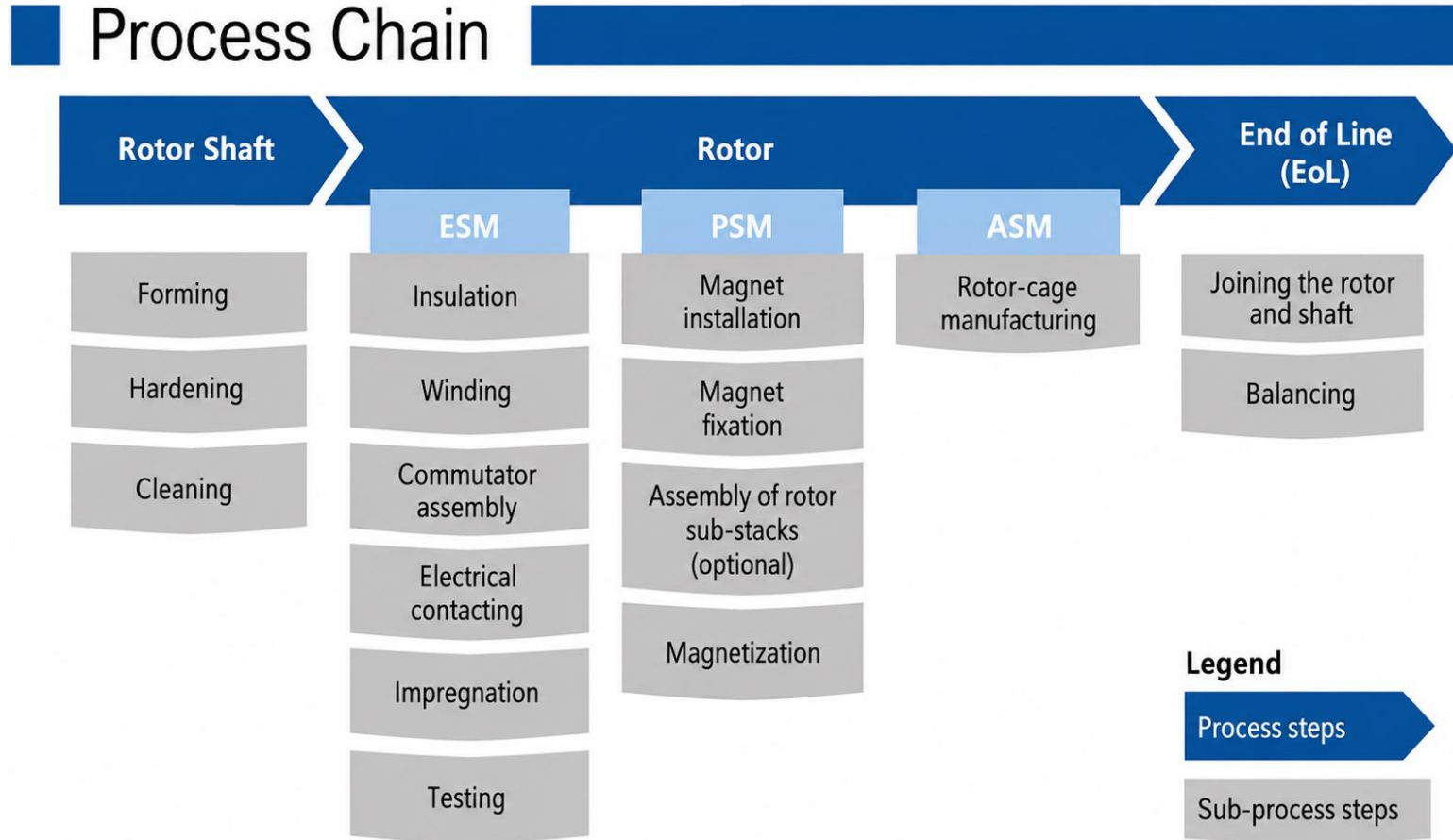
Rotor topologies: PSM, ESM and ASM

	Permanent-Magnet Synchronous Motor (PSM) Excitation principle - Permanent magnets are mounted inside or on the rotor and generate a constant magnetic field. <table border="1"> <tr> <td data-bbox="509 456 879 628"> Advantages - Higher power density - Higher efficiency </td><td data-bbox="879 456 1258 628"> Disadvantages - Higher material costs - Greater assembly effort when the magnets are already magnetized </td></tr> </table>	Advantages - Higher power density - Higher efficiency	Disadvantages - Higher material costs - Greater assembly effort when the magnets are already magnetized
Advantages - Higher power density - Higher efficiency	Disadvantages - Higher material costs - Greater assembly effort when the magnets are already magnetized		
	Externally Excited Synchronous Motor (ESM) Excitation principle - The teeth of the rotor lamination stack are wound in a manner similar to the stator. - The rotor winding is supplied with DC voltage through slip contacts or by inductive power transfer, thereby generating a constant electromagnetic field. <table border="1"> <tr> <td data-bbox="509 871 879 971"> Advantages - Controllable rotor magnetic field - Established production processes </td><td data-bbox="879 871 1258 971"> Disadvantages - Stochastic winding processes - Mechanical wear of the slip contacts </td></tr> </table>	Advantages - Controllable rotor magnetic field - Established production processes	Disadvantages - Stochastic winding processes - Mechanical wear of the slip contacts
Advantages - Controllable rotor magnetic field - Established production processes	Disadvantages - Stochastic winding processes - Mechanical wear of the slip contacts		
	Asynchronous Motor (ASM) Excitation principle - Copper or aluminium bars are short-circuited to form a rotor cage. - The rotating magnetic field of the stator induces current in the short-circuited cage, which generates an electromagnetic field. <table border="1"> <tr> <td data-bbox="509 1185 879 1322"> Advantages - No drag torque - Compact process chain </td><td data-bbox="879 1185 1258 1322"> Disadvantages - Lower efficiency - High process temperature during die casting </td></tr> </table>	Advantages - No drag torque - Compact process chain	Disadvantages - Lower efficiency - High process temperature during die casting
Advantages - No drag torque - Compact process chain	Disadvantages - Lower efficiency - High process temperature during die casting		

Three rotor types

- PSM – Permanent-magnet synchronous: magnets in/on the rotor give a constant field. High power density and efficiency; magnet material cost and magnetized-state assembly are the downsides.
- ESM – Externally-excited synchronous: a wound rotor is fed DC via slip rings. Controllable field and mature processes; slip-ring wear and stochastic winding remain challenges.
- ASM – Asynchronous (induction): a short-circuited cage in which the stator field induces current. No magnets, robust and compact, but lower efficiency and high die-cast process temperature.

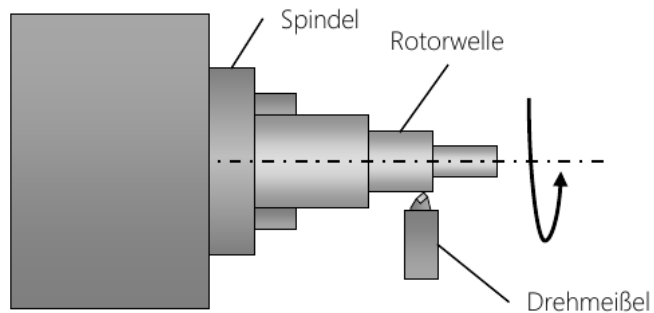
Rotor process chain by topology



Shared vs. specific

- Shared start: shaft forming, hardening and cleaning produce the rotor shaft.
- FSM branch: insulate, wind, mount commutator, contact, impregnate and test.
- PSM branch: magnet insertion, magnet fixing, optional sub-stack assembly and magnetization.
- ASM branch: produce the rotor cage (die-cast or welded).
- Shared end-of-line: join rotor to shaft and balance the assembly.

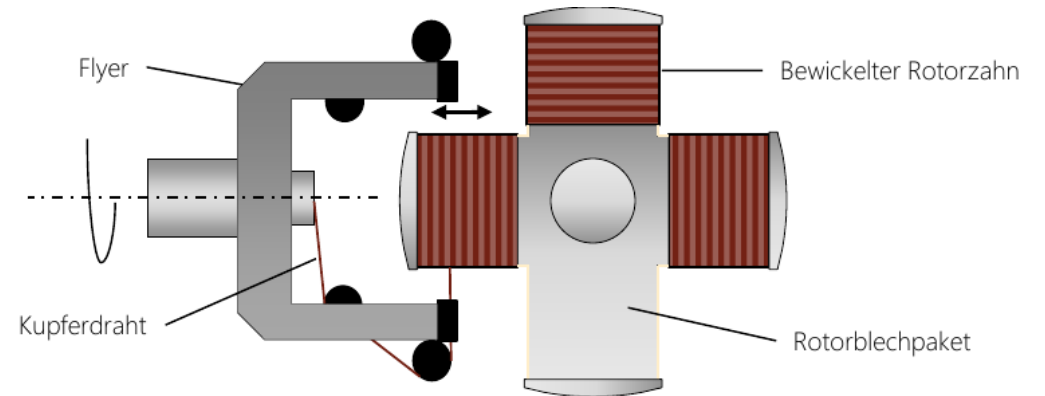
Rotor shaft and ESM winding



Turning the rotor shaft

Rotor shaft

- A solid or hollow shaft is turned to shape; functional surfaces (bearing seats) may be ground.
- Bearing seats and the torque-transmitting toothings are hardened, often by induction; the shaft is then cleaned.

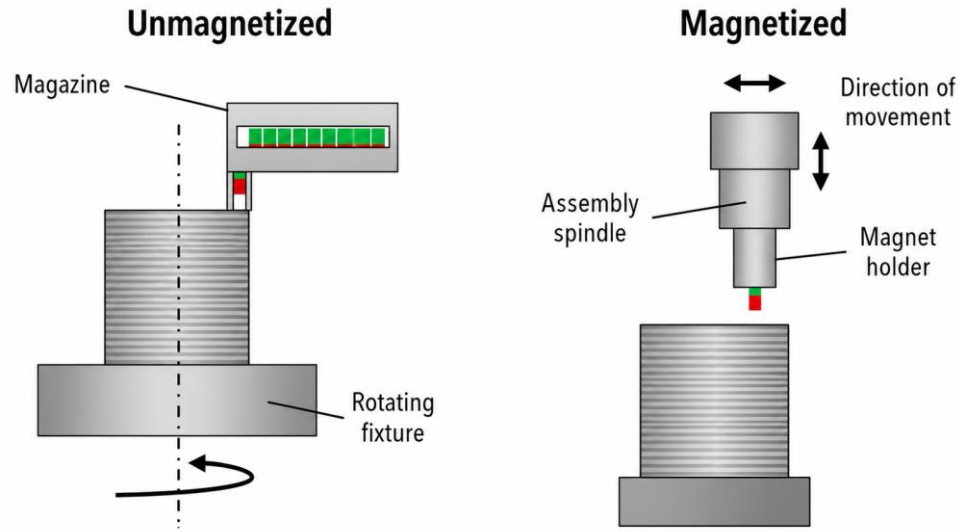


Flyer winding of the ESM rotor poles

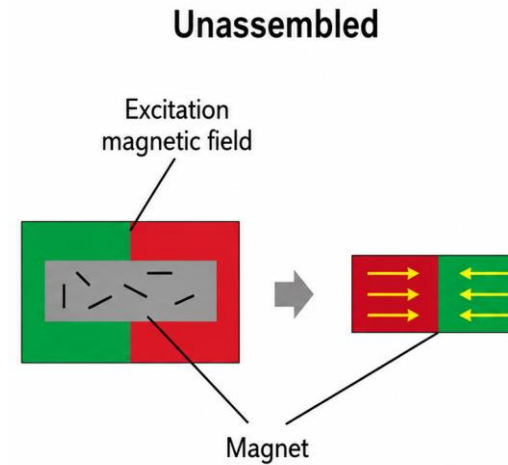
FSM winding

- Rotor poles are insulated, then wound: a flyer guides the copper wire onto each tooth.
- Concentrated windings are common for traction rotors; wire tension and bending forces drive quality.

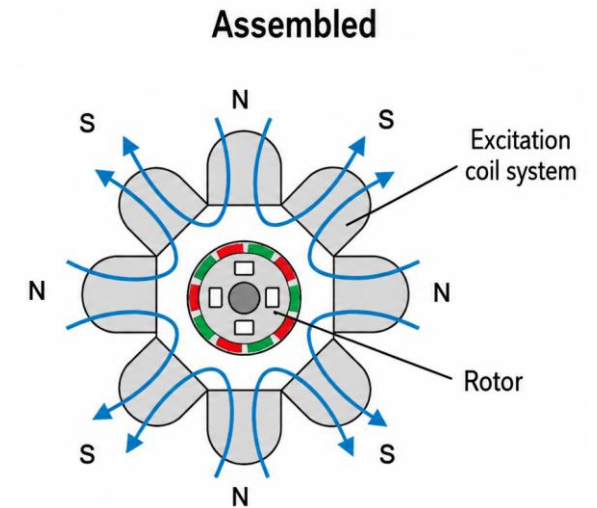
Permanent magnets: insertion and magnetization



Magnet insertion into the rotor core



Magnetizing the assembled rotor



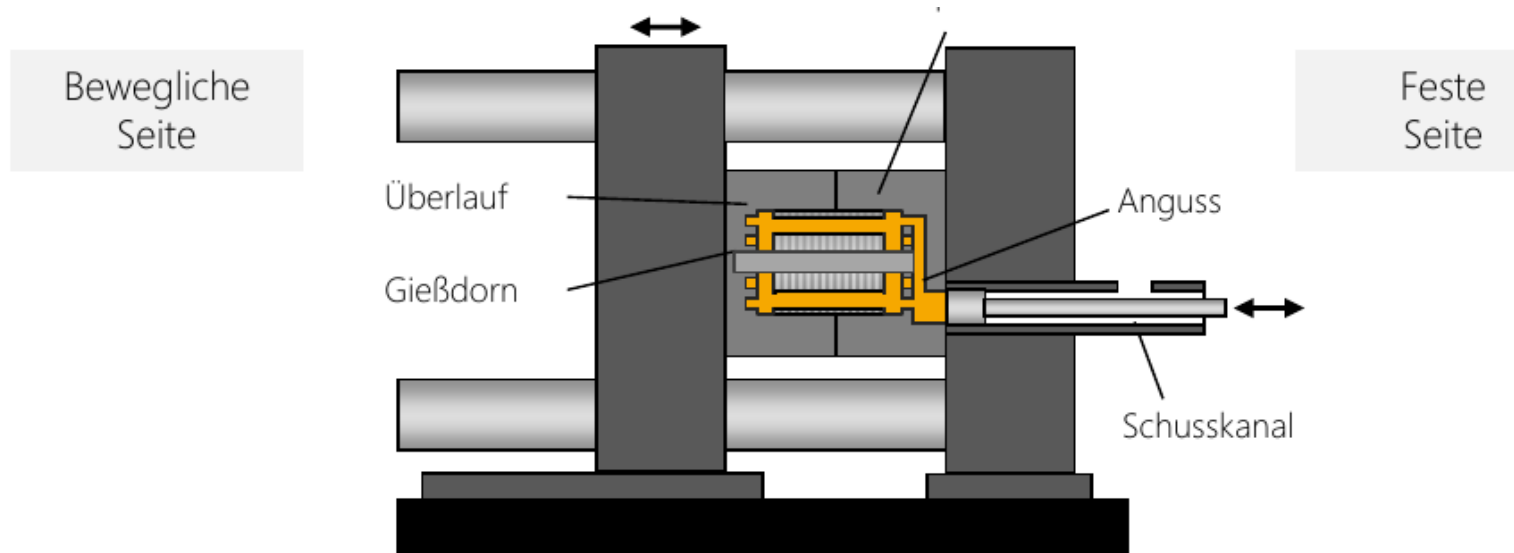
Insertion & fixing

- Magnets (often NdFeB) are placed — usually un-magnetized — into the slots of the rotor core.
- They are fixed by adhesive (1K/2K), cured with optional heating; bandaging or press-fits are alternatives.

Magnetization

- After assembly, an external excitation-coil field drives the magnets to saturation flux density.
- When the field is removed, remanence remains; inserting un-magnetized magnets eases handling and assembly.

The asynchronous rotor cage



Die-casting the rotor cage

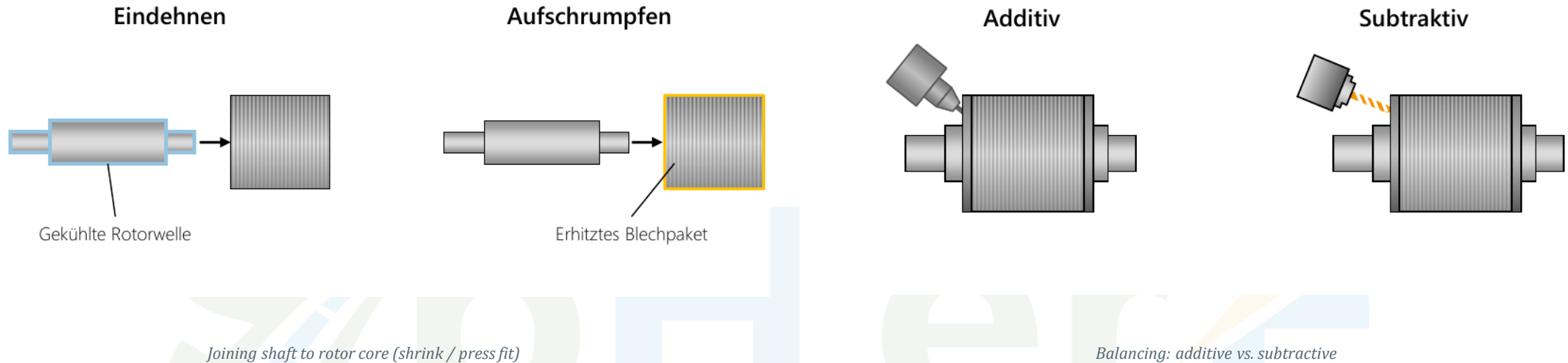
Two routes

- Die casting: molten copper or aluminium is shot under pressure into the pre-heated laminated package.
- The package is held in the mould for seconds; the gate is machined off and the bore prepared for the shaft.
- Welded cage: conductor bars are placed in the slots and joined to short-circuit rings by welding.
- Quality drivers: low porosity, good electrical contact and a high slot fill factor.

Why it matters

- The cage carries the induced rotor current — its conductivity and integrity set the machine's efficiency and thermal limit.
- Casting temperature and melt quality (pure Cu or Al) directly control porosity and contact resistance.

Joining the shaft and balancing the rotor



Joining shaft + core

- A press- or shrink-fit transmits torque: the shaft is cooled (N_2 , $< -196\text{ °C}$) or the core heated ($\sim 200\text{ °C}$).
- Temperature equalization creates the interference fit; gluing or welding are alternatives.

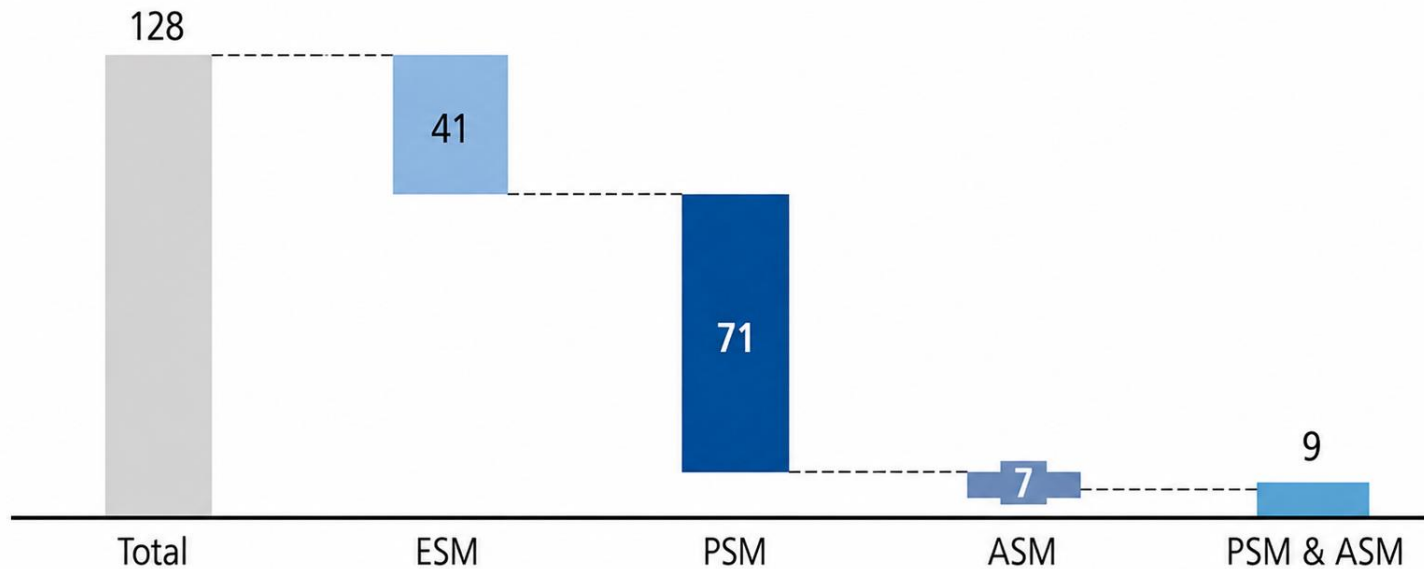
Balancing

- Residual unbalance (static and dynamic) is measured, then corrected by adding mass (welding) or removing it (drilling).
- Target balance grade follows DIN ISO 1940-1, set by application and operating speed.

Which motor topologies reach the road?

Motor Topologies in Use

Distribution of motor topologies among vehicle models in Germany*



Distribution of motor topologies across vehicle models in Germany (PEM survey, July 2022)

Topology shares

- PSM – 55 % market share: high power density and efficiency enable compact, powerful motor designs.
- ESM – 32 %: avoids rare-earth magnets at a slight efficiency penalty versus PSM.
- ASM – 5 %: rare-earth-free and cost-effective at high volume and high speed.
- Combinations (PSM & ASM) let a vehicle pair the complementary strengths of two designs.

KEY TAKEAWAYS

Electric motor manufacturing in a nutshell

- 1 An electric motor is a stator + rotor: the stator builds a rotating field; the rotor (PSM, FSM or ASM) follows it.
- 2 Stator production for traction drives is dominated by hairpin winding — a 15-step chain giving ~73 % slot fill, high currents and automation.
- 3 Rotor production shares shaft-making, joining and balancing, but branches by topology: magnets (PSM), wound poles (FSM) or a cast/welded cage (ASM).
- 4 Quality hinges on welding, insulation, magnet handling and balancing; PSM (55 %) leads the market, ahead of FSM (32 %) and ASM (5 %).

REFERENCES

PEM RWTH Aachen University & VDMA (Eds.). *Production Process of a Hairpin Stator*. 2nd print, Frankfurt am Main, March 2020. ISBN 978-3-947920-10-5. [link](#)
PEM of RWTH Aachen University (Eds.). *Produktionsprozesse von Rotoren* (Production Processes of Rotors). 1st ed., Aachen, October 2022. ISBN 978-3-947920-22-8. [link](#)

Sources

[1] Hairpin stator guide

- PEM RWTH Aachen University & VDMA (Eds.): Production Process of a Hairpin Stator. 2nd print, Frankfurt am Main, March 2020. ISBN 978-3-947920-10-5. [link](#)
- Authors: A. Kampker, H. H. Heimes, S. Kawollek, P. Treichel, A. Kraus (PEM); A. Raßmann, T. Hitzel (VDMA). — www.pem.rwth-aachen.de · www.vdma.org
- Figures used: stator structure, 15-step process chain, straightening / skinning / cutting / bending, inserting, twisting, laser contacting, stator test, cover hero (Slides 3–8).

[2] Rotor production guide

- PEM of RWTH Aachen University (Eds.): Produktionsprozesse von Rotoren (Production Processes of Rotors). 1st ed., Aachen, October 2022. ISBN 978-3-947920-22-8. [link](#)
- Authors: A. Kampker, H. H. Heimes, B. Dorn, F. Brans, M. Nankemann (PEM). — www.pem.rwth-aachen.de
- Figures used: rotor topologies (PSM/FSM/ASM), exploded view, rotor process chain, shaft, FSM winding, PSM magnet insertion & magnetization, ASM die-casting, joining, balancing, market chart (Slides 2, 9–15).