PRODUCTION PROCESSES OF ROTORS
Guide for electric motor production

In the series “Guide to E-Motor Production”, the Chair “Production Engineering of E-Mobility Components” (PEM) of RWTH Aachen University presents the process chains for manufacturing hairpin stators, continuous hairpin stators, and rotors.

Production Process of a Hairpin Stator
The “Production Process of a Hairpin Stator” guide covers the entire processes involved in the manufacture of hairpin stators as the predominant type for automotive traction applications, starting with wire straightening, through hairpin manufacture, assembly and interconnection, to impregnation and testing.

2nd edition
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PEM of RWTH Aachen University

Production Process of a Continuous Hairpin Stator
The “Production Process of a Continuous Hairpin Stator” guide presents continuous flat wire winding as an alternative to hairpin technology. Processes for manufacturing the winding mats and for inserting and interconnecting the windings are considered.

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Hrsg.
PEM der RWTH Aachen University

Production Processes of Rotors
The “Production Processes of Rotors” guide presents the process chain for manufacturing rotors for automotive traction applications. Alternative processes for the production of the three predominant designs (permanently excited and externally excited synchronous machine as well as induction machine) are discussed.

1st edition
Ed.
PEM of RWTH Aachen University
Radial Flux Machines
for automotive applications

General working principle
- In common radial flux machines, the rotor is usually arranged inside the stator.
- The stator windings are supplied with three-phase current and generate a rotating magnetic field.
- A magnetic field is also built up in the rotor, the properties of which differ depending on the excitation principle (PSM, EESM, IM – see below for explanations).
- The rotor follows the rotation of the stator magnetic field due to the interactions of the magnetic fields and rotates.
- In synchronous machines, the rotor speed is proportional to the rotational frequency of the stator field. Rotors of asynchronous machines follow the exciter field with a delay.

Rotor Topologies

**Permanently excited Synchronous Motor (PSM)**

**Exciter principle**
- Permanent magnets are mounted in or on the rotor and generate a permanent magnetic field.

**Advantages**
- Higher power density
- Higher efficiency

**Disadvantages**
- Higher material costs
- Increased assembly effort in magnetized state

**Externally excited Synchronous Motor (EESM)**

**Exciter principle**
- The teeth of the rotor laminations are wound in a similar way as the stator.
- The rotor winding is supplied with DC voltage via sliding contacts or inductively, and a constant electromagnetic field is generated.

**Advantages**
- Controllable rotor magnetic field
- Established production processes

**Disadvantages**
- Stochastic winding processes
- Mechanical wear of the sliding contacts

**Induction Motor (IM)**

**Exciter principle**
- Copper or aluminum bars are short-circuited to form a rotor cage.
- The rotating magnetic field of the stator induces current in the short-circuit cage, which ensures the build-up of an electromagnetic field.

**Advantages**
- No drag torque
- Compact process chain

**Disadvantages**
- Lower efficiency
- High process temperature in die casting
Design and Components of rotors for radial flux machines

Process Chain

Further Information

Structure (additions)
- Lamination stack with single metal sheets
- Resolver mounted on shaft (position encoder/speed encoder)
- PSM: magnets (plus adhesive or taping)
- EESM: windings (coil), sliding contacts
- IM: aluminum or copper cage
- Optional: balancing disc, circlip
- Materials: electrical sheet, enamelled wire, magnet material, insulation material

Quality requirements
- Magnetic field saturation and symmetry
- Torque ripple
- Freedom from damage (magnets, lamination stack, bearings)
- “Noise – Vibration – Harshness” (NVH): residual unbalance and balance quality
- Geometric and shape tolerances
- Cleanliness in production (freedom from chips)
- Small air gap (physically at least approximately 0.2 mm possible)
In the manufacture of the rotor shaft, a shaft element (solid or hollow shaft) is given its shape by classic metal-cutting turning. For functional surfaces, such as bearing seats, machining by grinding can also be performed.

Functional elements such as the gearing for transmitting the rotor torque to the rest of the powertrain are installed.

The bearing seats are hardened, e.g. by induction hardening processes.

If necessary, the surfaces are subsequently machined.

Finally, the rotor shaft is cleaned.

**Further Information**

**Alternative technologies [excerpt]**

- Flowforming: inductive heating and forming in the heated state, suitable for manufacturing the rotor as a hollow shaft
- Hollow or solid shaft design: Hollow shafts offer the potential of significant weight reduction and the possibility of cooling

**Quality features [excerpt]**

- High surface quality for tangential loads due to torque and radial loads due to rotor weight
- Dimensional accuracy for error-free assembly
- Resistance to water-glycol mixtures and oil when using a rotor-internal cooling system

**Quality impacts [excerpt]**

- Shaft must be designed to be temperature-stable, as the rotor heats up during operation (max. 180°C)
- External force influences (tangential as well as radial) require high adherence to form tolerances (cylindricity, roundness, roundness and straightness)
Externally excited Synchronous Machine

Design and components

Production Process

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<td>Insulation of the manufactured poles (to accommodate the coils later)</td>
<td>Winding of the poles (coil production)</td>
<td>Assembly the commutator</td>
<td>Connection of the copper slip rings (commutator) that are connected to the DC source</td>
<td>Testing of the windings by test current or inductive test methods</td>
</tr>
</tbody>
</table>

Further Information

Design
- Generation of a rotating magnetic field by energizing the stator windings
- Generation of a constant magnetic field in the rotor by transmission of direct current

Operating principle
- Generation of a magnetic field by direct current (via slip rings)
- Energy conversion: efficiency of 0.85 to 0.95

Advantages
- No permanent magnets required, thus more cost-effective
- Simple construction
- Higher functional safety
- Good efficiency over operating range

Disadvantages
- A slip ring is needed to transmit the electrical energy, causing wear and abrasion in the air gap.
- Lower volumetric and gravimetric power density
Process Description

• The lamination stack must be electrically as well as mechanically separated from the winding to avoid electrical contact due to both material defects and assembly damage.
• The insulation paper or laminate is cut to the length of the lamination stack – with overhang, if necessary.
• The surface insulation material is folded according to the slot geometry and inserted into the rotor slots.
• If necessary, the correct positioning of the paper is ensured by a slider.
• Additional insulation elements (cover caps, cover slides) are mounted after the winding has been inserted.

Further Information

Alternative technologies [excerpt]

• Overmolding
• Injection molding and assembly
• Powder coating

Quality features [excerpt]

• Electrical insulation strength
• Mechanical filling level or wetting
• Overhang or overmolding of insulation material
• No damage during or after insertion
• Thermal conductivity and flexibility

Quality impacts [excerpt]

• Insertion speed/frequency/force
• Injection pressure, temperature, number of molds injected simultaneously
• Insulation material thickness
Process Description

- In the production of externally excited synchronous machines, the coils for generating the magnetic field are wound onto the rotor poles.
- The enameled copper wire is fed through the so-called flyer with the help of wire clamps and placed on the rotor lamination stack’s tooth to be wound.
- For even distribution, the flyer is moved back and forth, and the wire is guided over guide jaws, if necessary.
- The wires are then cut, and the wire ends are fixed.
- Depending on the coil former geometry, both concentrated and distributed windings are possible. Concentrated windings are common in rotors for traction applications.

Further Information

Alternative technologies [excerpt]
- Linear winding
- Needle winding

Quality features [excerpt]
- Filling factor (electrical/mechanical)
- Damage to the paint insulation of the wire
- Interconnection effort after completed winding

Quality impacts [excerpt]
- Wire tensile and wire bending forces
- Winding speed
- Traverse paths of the winding tool
- Rotation speed of the tool
EESM: Commutator Assembly

Process Description

- The commutator, which enables continuous energization of the rotor, is joined to a shoulder of the rotor shaft in an axial joining process.
- The commutator is fixed to the rotor shaft by means of an interference fit created by pressing the oversize rotor shaft into the commutator.
- The energization unit including the carbon brushes is usually screwed into the housing after the rotor and stator have been mounted.

Further Information

Alternative technologies [excerpt]
- Cold expansion by cooling the rotor shaft
- Bonding of the commutator to the rotor shaft
- Positive connection with feather key or serration

Quality features [excerpt]
- Stable mechanical connection between commutator and rotor shaft
- High positioning accuracy and concentricity

Quality impacts [excerpt]
- Mechanical or thermal load on the rotor shaft
- Joining force
- Joining speed
EESM: Contacting of the winding ends

Process Description

- Depending on the winding scheme, the first step is to realize electrical contact between the individual winding strands, which may also be parallel.
- The winding and the commutator are electrically connected by soldering.
- Usually, end plates are mounted axially for mechanical fixation and protection of the winding.
- The contacting of the power supply unit with the power electronics, via which the commutator is supplied with current, takes place at the end of the motor assembly.

Further Information

Alternative technologies [excerpt]
- Clamping
- Laser welding
- Resistance welding
- (Hot) Crimping

Quality features [excerpt]
- Electrical resistance of the connection
- Low solder residue or weld spatter
- Mechanical strength of the connection
- Corrosion resistance

Quality impacts [excerpt]
- Temperature of the contact point
- Soldering temperature and time
- Energy input
EESM: Impregnation of the windings

Process Description

- Rotor and resin are heated before application.
- The impregnating resin is applied to the windings.
- Slot penetration takes place according to the principle of the capillary effect.
- To ensure uniform distribution of the resin within the rotor, the rotor – including clamp – rolls continuously.
- Gelling, curing and cooling take place in different plant sections and at individual temperature profiles.

Further Information

Alternative technologies [excerpt]

- Resin application: trickling, roll dipping/rolling, hot dipping, vertical dipping, full potting
- Heat input: convection, induction, current heat, infrared, ultraviolet (UV) radiation
- Additionally: weight control before and after the process to determine the resin uptake; camera monitoring for application control

Quality features [excerpt]

- High fill factor (especially in the slot)
- Avoidance of unfilled cavities
- High thermal conductivity
- Little rework required for cleaning
- Aging resistance
- No damage on the lamination stack

Quality impacts [excerpt]

- Process temperature profile
- Application quantity of the resin
- Resin temperature profile
- Rotation speed
- Continuity/synchronization of rotation
- Slot geometry
Process Description

- To ensure function, an electrical test of the lamination stack and winding is carried out.
- In the lamination stack, faults in the insulation generally lead to low motor efficiency due to increased losses (eddy current losses) or to short circuits.
- Insulation testing of the lamination stack is performed using an external magnetic field, while measurement of the magnetic field strength after passing through the lamination stack is performed by using Hall sensors.
- Insulation testing of the winding is carried out, for example, by means of a surge voltage test at different system boundaries (winding insulation, phase insulation, ground insulation) to detect insulation faults between conductors, phases, winding, and lamination stack.
- A resistance test by means of DC voltage measurement against ground is used to check the winding and contacting resistances.

Further Information

Alternative technologies [excerpt]
- Insulation test of the lamination stack
- Insulation test of the winding, surge voltage test
- Partial discharge test
- High voltage test
- Resistance test

Quality features [excerpt]
- Insulation strength lamination stack/winding
- Insulation fault lamination stack/winding
- Winding and contact resistance

Quality impacts [excerpt]
- Material selection
- All upstream processes including handling
Permanently excited Synchr. Machine

**Design and components**

- **Stator lamination stack**
- **Stator coil**
- **Assembled magnet**
- **Shaft**
- **Rotor lamination stack**
- **Surface magnet**

**Production Process**

<table>
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<tr>
<th>Magnet assembly</th>
<th>Magnet fixation</th>
<th>Magnetization</th>
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<tr>
<td>Magnets are inserted magnetized or non-magnetized into the slots provided for this purpose in the rotor lamination stack</td>
<td>Fastening of the permanent magnets mostly by means of a substance-to-substance connection</td>
<td>Application of a strong external magnetic field through a coil, resulting in irreversible alignment of magnetic spins in permanent magnets</td>
</tr>
</tbody>
</table>

**Further Information**

**Design**

- Generation of a rotating magnetic field by energizing the stator windings
- Generation of a temporally constant magnetic field by permanent magnets
- Commonly used magnetic raw material is NdFeB

**Operating principle**

- Permanent magnetic field (due to permanent magnets)
- Energy conversion: efficiency of 0.95 to 0.98

**Advantages**

- Compact design with low weight thanks to high power density
- Higher range of electric vehicles due to higher efficiency with the same battery capacity

**Disadvantages**

- Required magnetic materials are limited resources
- Assembly of the magnets in magnetized state is comparatively complex
PSM: Magnet Assembly

Insertion of the magnets

**Process Description**

- In preparation for the assembly of the magnets into the rotor lamination stack, the magnets are provided in an unmagnetized state in a magazine.
- The rotor lamination stack is fixed on a rotary table, and the first magnet slot is positioned under the feeder element.
- If necessary, an additive to fix the magnets in the lamination stack is applied to the magnets or in the slots of the lamination stack.
- The magnets are then deposited from the magazine into the slots, and the lamination stack is rotated to the next slot position.
- Finally, the loaded rotor is removed automatically or manually.

**Further Information**

**Alternative technologies [excerpt]**

- Robotic direct assembly
- Joining with joining spindle

**Quality features [excerpt]**

- High cycle rate
- High positioning accuracy
- No damage of the magnets

**Quality impacts [excerpt]**

- Lower saturation during magnetization following assembly
- Increased effort when mounting already magnetized magnets
PSM: Magnet Fixation
Gluing of the magnets

Process Description

- An adhesive (1K or 2K) is applied manually or automatically to the magnet or applied to the slots of the rotor lamination stack.
- The magnets are inserted manually or by an automated joining unit into the slots of the rotor lamination stack.
- Curing takes place at temperatures between 20°C and 200°C, depending on the crosslinking mechanisms of the adhesive.
- By heating the adhesive, the process time can usually be significantly reduced with additional energy input.

Further Information

Alternative technologies [excerpt]
- Resin Transfer Molding
- Caulking
- Bandaging
- Expanding matrix
- Interference fit
- Tensioning and clamping elements

Quality features [excerpt]
- Homogeneous and areal distribution of the adhesive
- High mechanical strength
- High running smoothness
- Temperature resistance
- Low energy input

Quality impacts [excerpt]
- Respective dosing system
- Adhesive residues in the machine system
- Temperature profile during curing
PSM: Magnetization of the permanent magnets

Process Description

• Magnetization of the magnets is often carried out following assembly using multi-coil exciter systems.
• The rotor (usually already with shaft) is placed in the exciter coil system, and an external magnetic field is applied so that the saturation flux density $B_s$ is achieved in each magnet.
• For the best possible saturation of the magnets, with simple and near-surface magnet arrangements up to the saturation flux density, a variant-specific magnetizer design is necessary.
• As soon as the necessary saturation is reached, the excitation field is reduced. A magnetic field with the material-specific flux density "remanence $B_R$" remains in the magnets.

Further Information

Alternative technologies [excerpt]

• Placement of individual unmagnetized magnets in a coil assembly with a simple excitation magnetic field
• Application of the external magnetic field until the saturation flux density in the magnet material is reached
• Removal of the magnetized magnets and subsequent assembly in the rotor

Quality features [excerpt]

• Achieved remanence $B_R$
• Energy required to apply the necessary field strength for each magnet

Quality impacts [excerpt]

• Position of the magnets in the lamination stack
• Hysteresis behavior of the magnet material used
Induction Machine

Production Process

Process alternative “die casting”
- Molten copper or aluminum is injected under pressure directly into the sheet package.

Process alternative “welding”
- Bar sections are mounted into the laminated core and connected with short-circuit rings to form a cage.

Further Information

Design
- Current is induced by the rotating field generated by the stator.
- Induced current creates a magnetic field that interacts with the stator’s magnetic field to create torque.

Operating principle
- Generation of a temporary magnetic field by self-induction
- Energy conversion: efficiency of 0.92 to 0.96

Advantages
- Low cost and higher torque than DC motors
- No permanent magnets required
- Technically least complex while robust in operation

Disadvantages
- Lower power density and efficiency than PSM
- Increased heat development
IM: Die Casting of the rotor cage

**Process Description**

- The lamination stack is placed on a casting pin and preheated in the furnace with it.
- A solvent is applied to the warm mold (preheated or process heat).
- The lamination stack is inserted into the mold by robot, and the mold is closed.
- The channel is filled with the casting material—usually pure copper or aluminum.
- The clamping force is applied, the casting material is injected into the lamination stack via the channel of ascent, and the mold is held closed for a few seconds.
- The lamination stack with rotor cage is removed and cooled in an immersion tank, if necessary.
- The sprue is cut off by machining, the casting pin is removed in a press, and the rotor shaft is inserted, if necessary.

**Further Information**

**Alternative technologies [excerpt]**

- Production of conductor rods and welding with short-circuit rings after assembly
- Production of semi-finished rotor cages (die casting) and welding with a short-circuit ring after assembly
- Soldering of the rodded rotor cage

**Quality features [excerpt]**

- Low porosity in the cast cage
- High mechanical strength of the rotor
- High temperature and wear resistance of the tool

**Quality impacts [excerpt]**

- Slot cross-section and length of the lamination stack as limiting factors for casting quality
- Stable process control during the casting process (shot speed, temperature of the melt, etc.)
- Casting material copper or aluminum
**IM: Welding of the rotor cage**

### Process Description

- From a bar profile – usually pure copper or aluminum – conductor rods are manufactured in the length of the lamination stack with a slight overhang.
- The short-circuit ring is built up in segments from individual discs produced in a stamping process.
- The short-circuit ring is applied to the end faces of the package, which can be done either directly during the packaging of the lamination stack or following the bar assembly.
- The lamination stack is clamped, and the conductor bars are inserted into slots provided for this purpose in the rotor lamination stack.
- The short-circuit rings are joined to the conductor bars by welding.

### Further Information

#### Alternative technologies [excerpt]

- Die casting of the entire rotor cage (including the laminar squeeze casting process)
- Production of semi-finished rotor cages (die casting) and welding of a short-circuit ring after assembly
- Soldering the rodded rotor cage

#### Quality features [excerpt]

- Low porosity in the conductors
- Good electrical contacting of the short-circuit ring
- High electrical slot fill factor
- Requirement-oriented composition of the short-circuit ring (mechanical strength, conductivity, etc.)

#### Quality impacts [excerpt]

- Cleanliness of contact points before welding process
- Welding process control
- Thermal influence due to the joining process
Joining Shaft in rotor pack

Process Description

- The rotor is mounted on the rotor shaft so that it cannot rotate so that the generated torque can be transmitted to the shaft.
- In most cases, the frictional connection between the lamination stack and the rotor shaft is produced by thermal joining (stretching or heat shrinking).
- Expanding: The rotor shaft is cooled in a nitrogen bath (temperature: < -196 °C) so that the volume of the shaft is reduced and the shrunken shaft can be joined into the lamination stack.
- Afterwards the shaft is expanding while heating up to room temperature.
- Heat shrinking: The lamination stack is usually heated inductively to a temperature of around 200°C so that the lamination stack expands thermally and can be joined onto the rotor shaft.
- The subsequent temperature compensation between rotor shaft and lamination stack results in a shaft-hub connection by press fit.

Further Information

Alternative technologies [excerpt]

- Joining by frictional connection: Pressing the shaft into the lamination stack creates a frictional connection between the rotor shaft and the lamination stack.
- Joining with the aid of a feather key: positive connection by mounting a feather key
- Joining by bonding: The rotor laminations are glued to the shaft. The adhesive becomes warm during the chemical reaction.
- Joining by welding: The shaft is inserted into the rotor laminations. Both components are then circumferentially welded.

Quality features [excerpt]

- Little change in material properties
- High mechanical stability of the connection
- Compliance with shape and position tolerances

Quality impacts [excerpt]

- Heating or shrinkage can lead to structural changes and irregular warpage
- No damage-free disassembly
- Consideration of axial securing during joining with the aid of a feather key
Balancing of the entire rotor

Process Description

• To prevent bearing damage and minimize noise and vibration, the entire rotor system is balanced in the final process step.
• The existing unbalance, both static and dynamic, is detected via an unbalance measurement.
• The unbalance is corrected by applying or removing mass to or from the rotor system at balancing discs provided for this purpose or directly at the lamination stack.
• Depending on the application and operating speed, different balancing grades must be achieved (DIN ISO1940-1:2004-04).

Further Information

Alternative technologies [excerpt]
• Additive balancing: Spot mass is added to the overall system at defined points; example: buildup welding.
• Subtractive balancing: Mass is removed from the entire system at defined points; example: holes drilled in the balancing disc or in the lamination stacks.

Quality features [excerpt]
• Unbalance (mass and radius)
• Position of the unbalance
• Rotational speed
• Eccentricity
• Low weight for compensation

Quality impacts [excerpt]
• Targeted balancing qualities
• Dynamic or static unbalances
• Mass of the unbalance
Radial Flux Machines in automotive applications

Current market overview

- An analysis of the vehicle market in Germany shows that, at present, permanently excited synchronous machines are primarily used.
- The system output of the models currently available in Germany or announced for 2022 varies between 33 kW and 828 kW.
- The use of multiple electric motors per vehicle is becoming increasingly established.
- By using different engine designs in one vehicle, topology-specific properties can be combined.

Motor Topologies in Use

Distribution of engine topologies by model in Germany*

- Total: 128
- EESMs: 41
- PSMs: 71
- IMs: 9
- PSM & IMs: 7

Use of EESMs
- Current market share: 32%
- EESMs can be used to avoid rare earth metals at slightly reduced efficiency compared to PSMs.

Use of PSMs
- Current market share: 55%
- The high power density and high efficiency make compact and powerful motor designs possible.

Use of IMs
- Current market share: 5%
- IMs are free of rare earth metals and are a low-cost alternative for high volumes with high efficiency in the high speed range.

Use of IMs & PSMs
- Current market share: 7%
- By combining IMs and PSMs, the properties of the two construction methods can be used in a complementary manner.

* Vehicle models available or announced for 2022, own research (July 2022).
The “Production Engineering of E-Mobility Components” (PEM) Chair of RWTH Aachen University was founded in 2014 by “StreetScooter” co-inventor Professor Achim Kampker. In numerous research groups, the team is dedicated to all aspects of the development, production and recycling of battery systems and their components as well as the fuel cell and the production of the electric powertrain and entire vehicle concepts. PEM’s focus is always on sustainability and cost reduction – with the goal of a seamless “Innovation Chain” from basic research to large-scale production in the immediate vicinity.

The research group “Electric Drive Production” at PEM contributes to the economic, variant-flexible, future-oriented and sustainable production of the electric drive and its active components (rotor and stator). The focus is on the investigation of issues along the entire value chain – from the semi-finished product to the finished drive and from the individual process to the holistic consideration of cross-process interactions. In line with the PEM philosophy, the team works on innovative technologies, always keeping an eye on the path to industrial application and solution scaling.