PRODUCTION PROCESS OF A CONTINUOUS HAIRPIN STATOR

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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.

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Ed.
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. Among other things, the processes for manufacturing the winding mats and for inserting and interconnecting the windings are considered.

1st edition
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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 separately excited synchronous machine as well as asynchronous machine) are discussed.

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Wave Winding

Basics & features

- Wave winding or "continuous hairpin technology" is a winding variant for solid profile wires, square or rectangular, usually made of copper.
- The winding wire is bent or wound into U-shaped alternating winding mats and then inserted into the stator slots of the lamination stack.
- As in the conventional winding or forming coil techniques, the lamination stack consists of stacked electrical sheets insulated from each other (sheet thickness: 0.18 mm to 0.5 mm).
- Analogous to the shaped coil technology, the shaft winding offers the advantage of a high copper filling level in the stator slots as well as good automatability of the production process.
- Compared to U-hairpin technology, continuous hairpin winding allows extremely low winding head heights on both sides, as the contacting process is largely eliminated.
- With continuous hairpin technology, a mechanical slot filling factor of up to 90% can be achieved.
- Continuous hairpin winding combines the advantages of classic round wire winding techniques with those of shaped coil techniques.
- The technology can be used efficiently in large-scale production for traction and auxiliary drives.
- The requirement of the technology is a large diameter-length ratio of the stator under the constraint of limited flexibility in the winding scheme.

Design and Components of a continuous hairpin stator

- Power: 80 - 300 kW
- Inner diameter stator: ≥ 100 mm
- Active stator length: 30 - 200 mm
- Large diameter-length ratio
- High number of stator slots: ≥ 48
- High number of pole pairs (10, 12, 14...)
- Number of conductors per slot: 6 - 14 (20)
- Slot filling factor (mechanical): up to 90%
- Slot filling factor (electrical): up to 70%
Requirements and limitations of the technology

<table>
<thead>
<tr>
<th>Requirements and limitations for the lamination stack</th>
<th>Requirements and limitations for the winding wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Requires a radially open stator slot to allow insertion of the winding, which is why no pronounced pole shoes are possible.</td>
<td>• High forming forces during mat manufacture and assembly stress the wire insulation.</td>
</tr>
<tr>
<td>• The accessibility of the slot opening for inserting the winding is approximately the winding wire width plus 0.4 mm.</td>
<td>• Joining tolerances and springback tendency of the copper conductor require a forced guidance of the winding mat.</td>
</tr>
<tr>
<td>• Eddy current losses, cogging torques and NVH behavior are slightly negatively affected by the slot geometry.</td>
<td>• The large number of relative movements between tool and winding wire requires polished surfaces when they are in contact with the component.</td>
</tr>
<tr>
<td>• The slot opening can be subsequently closed with cover slides to fix the winding.</td>
<td>• The introduction of force into the forming and assembly process often takes place indirectly via several wire layers.</td>
</tr>
<tr>
<td>• Segmentation of the lamination stack reduces the electromagnetic utilization of the active length to approximately 97%.</td>
<td>• Mechanical requirements are only met to a limited extent with current wire coatings such as PAI or PI.</td>
</tr>
</tbody>
</table>

Process Chain of continuous hairpin stator production*

1. Straighten copper wire
2. Strip copper wire
3. Wrap and shape mat
4. Cut copper wire to length
5. Insulate stator slots
6. Insert winding mat
7. Insert cover slide
8. Interconnect winding ends
9. Impregnate stator
10. Stator test

* Generic process chain. Process sequence can vary depending on technology and product.
Straighten Copper Wire

Process Description

- The enameled copper wire is supplied on a copper wire reel.
- Winding the copper wire onto the coil results in curvatures in the wire structure that have to be corrected for the further process steps.
- In multi-stage straightening, the wire is straightened in several steps by appropriate tools (in two axis directions) to remove the residual curvature.
- The exact straightening of the rectangular copper wire leads to an increase in positioning accuracy during assembly, setting and welding of the hairpins in downstream process steps.
- The design of the straightening process is significantly influenced by the material properties of the wire and must therefore be continuously controlled and adapted if necessary.

Further Information

Alternative technologies [excerpt]

- Stretch straightening
- Stretch bending straightening
- Additionally: inline and offline control of the wire before and after the process

Quality features [excerpt]

- Straightness
- Low (residual) curvature
- Low superelevation
- Shape tolerances: cross-section changes
- Low wire damage
- Low level of impurities

Quality impacts [excerpt]

- Low level of impurities
- Material springback and yield strength
- Wire feed speed/continuity
- Material handling
- Residual stress state
- Tool stiffness
Strip Copper Wire

Process Description

- The winding of a stator with continuous hairpin winding consists of several parallel conductor strands which are to be contacted with each other according to the winding diagram.
- The insulation layer on the copper wire is partially removed by the rotating tool movement of high-speed cutters and with the feed of the wire.
- The cutters are to be designed as form cutters to ensure full removal of the wire insulation also in the radii.
- The area to be stripped is defined by the synchronized infeed stroke of the cutters.
- The feed stroke of the cutters adjusts the stripping depth according to the wire dimension and insulation layer thickness including compensation of geometry tolerances.
- When stripping by milling, there is always a small amount of copper removal.

Further Information

Alternative technologies [excerpt]
- Laser-based methods
- Mechanical methods
  - Grinding
  - Scraping

The stripping process step can also take place after the mat has been produced and/or inserted into the coil end.

Quality features [excerpt]
- Stripped area: low insulation residue (RFU <10)
- Positioning accuracy of the stripping
- Avoidance of “fringing” on the insulation
- High repeatability/process reliability

Quality impacts [excerpt]
- Cutting speed/speed of rotation
- Feed rate
- Wear on the cutting edges
- Wire guide and oscillating capacity
- Direction of rotation
- Conductor and insulation material
**Wrap and Shape Mat**

**Process Description**

- Several wires are wound in parallel around a rotating winding sword as a linear winding process with a translating wire nozzle (sword winding technology).
- To avoid twisting of the wire in the coil end, its orientation must always be accurately guided by the rotation of the wire nozzle.
- This is followed by demolding of the winding mat and, if necessary, postforming of the wire mat for compacting the coil end and layering the winding mat.
- Stretching of the winding by varying the winding width and phase jump by changing the position of parallel winding wires is possible.
- The winding mat can be several meters long, depending on the stator size and number of layers.

**Further Information**

**Alternative technologies [excerpt]**

- Flat winding technology (winding technology)
- Woven winding mat (layering technology)
- Layered winding mat (layering technology)
- Mounted winding mat (layering technology)

**Quality features [excerpt]**

- Coil end height and diameter
- Linearity of the stator axis-parallel wire strands
- Freedom from damage of the conductor insulation
- Sword winding technology: twisting state
- Illustration of the winding scheme

**Quality impacts [excerpt]**

- Occurring process forces
- Residual stress state of the wire body
- Conductor cross-section shape/dimension, paint insulation layer thickness/elasticity
- Bending radii and target bend shape at the coil end
- Surfaces in contact with the workpiece
**Wrap and Shape Mat**

**Winding technology: alternatives**

**Flat winding technology**
- Wire-individual 2D/3D bending of a meander pattern
- If necessary, subsequent 3D shaping of the head shape by embossing
- Assembly of the single wires to the winding mat
- Lower process forces and wire loads

**Layering technologies: alternatives**

**Woven mat**
- Conductor strands interwoven in parallel winding process with undercut (sword winding process)
- Reshaping of the mat necessary
- Stretching of the winding possible by variation of the winding width
- Phase jump due to alternation of parallel winding wires

**Stacked mat**
- Individual wire strands are stacked linearly on top of each other
- No inherent dimensional stability of the mat
- Variations in the winding scheme mainly possible via the winding width

**Mounted mat**
- Multi-axis assembly movement of the wire strands to each other (flat winding)
- Compact and rigid wrapping mat
- Uniform distribution of potentials over the winding scheme requires a winding scheme according to fixed set of rules
Process Description

- The individual strands of the winding mat are cut to the required wire length after the winding process.
- The shear cutting process consists of four phases:
  - Elastic deformation
  - Plastic deformation
  - Plastic flow
  - Crack formation
- The cutting process must be adjusted in such a way that deformation of the wire cross section and burr formation are avoided as far as possible.

Further Information

Alternative technologies [excerpt]

- Shear cutting
- Knife cutting
- Bite cutting
- Tearing
- Tear-in

The process step of cutting to length can optionally be done before the mat winding process, and the mat can be formed from the already cut wire sections.

Quality features [excerpt]

- Position tolerance (positioning of the cut)
- Cutting burr
- No damage to the conductor insulation
- No deformation of the wire cross section

Quality impacts [excerpt]

- Semifinished product properties
- Hold-down force
- Cutting gap in relation to material thickness
- Wear condition of the cutting tools
- Cutting speed
Insulate Stator Slots

Process Description

• The copper winding is separated from the ground potential of the lamination stack by using slot insulation paper.
• Manual or fully automated cutting and folding of the insulation paper is possible.
• Axial or radial insertion of the slot base insulation is possible.
• Constant synchronization of the material feed, the timing of the insertion or injection, the forming force and kinematics during the forming and lining of the slots is required.
• The insulation paper can be made in U- and O-shape, where the closing of the O-shape takes place after the insertion of the winding mat.
• The inspection for damage as well as wrinkle freeness is done manually or automatically.

Further Information

Alternative technologies [excerpt]

• Plastic injection molding: insulation of the slots with a process similar to injection molding
• Powder insulation: application of powder resins or varnishes and subsequent curing
• Abandonment of slot insulation paper (higher requirements for other insulation systems)

Optional: Additional surface insulation in the coil end can be inserted into the winding as supplementary phase insulation.

Quality features [excerpt]

• Shape and position deviation of insulation
• Freedom from damage at axial end edge of stator lamination stack
• Freedom from cracks and wrinkles
• Air pockets (slot insulation/stator lamination stack)
• Defined slot paper protrusion

Quality impacts [excerpt]

• Stator geometry (slot geometry and length)
• Folding scheme
• Lining and winding process
• Insertion speed
• Forming force
**Process Description**

- The winding mat is inserted radially from the inside of the stator into the slots of the lamination stack, with the assembly process being superimposed by a forming process of the winding mat (upsetting and stretching).
- The winding mat is rolled up on a buffer (one or more wire mats, depending on the winding mat arrangement).
- The buffer is inserted axially into the inside of the lamination stack.
- The winding is inserted into the slots of the stator laminations by radial expansion (axial compression of the coil ends due to the necking effect).
- It may be necessary to press the winding into the bottom of the slot.

**Further Information**

**Alternative technologies [excerpt]**

- Helical expansion
- Spiral expansion
- Insertion of the winding mat by compression into externally grooved lamination stacks
- Assembly of the winding mat into segmented lamination stacks

**Quality features [excerpt]**

- Homogeneity of the individual winding layer heights/coil ends
- Radial coil end width
- Axis parallelism of the coil ends (minimal inward curvature, if possible)
- Freedom from damage of the paint insulation

**Quality impacts [excerpt]**

- Occurring process forces
- Winding mat arrangement
- Material properties and wire forming grade
- Effective stator slot opening width (nominal wire width plus 0.4 mm)
- Elasticity/springback of the wire mat
Process Description

- Fixation of the winding mat in the radial direction of the stator slot and termination of the insulation system is achieved by inserting a cover slide made of an insulation material.
- The cover slide is cut from a flat or molded material, folded and reshaped if necessary, and then inserted into the slots.
- Re-pressing the winding to position it in the slot base may be necessary.
- The cover slide can be mounted axially or radially in the stator slot.
- Fixation is possible by frictional or positive locking, whereby the slot geometry and the slot base insulation must be designed geometrically accordingly.

Further Information

Alternative technologies [excerpt]

- Abandonment of the cover slide
- Socketing of the slot
- Combination with slot base insulation by flipping slot paper wings

Quality features [excerpt]

- Shape and position deviation of the cover slides
- Freedom from damage of the cover slide
- Freedom from cracks and wrinkles
- No interference with the rotor gap space
- Defined cover slide protrusion

Quality impacts [excerpt]

- Stator geometry (shape and length)
- Required fixation force of the winding
- Insertion speed
- Geometric inaccuracies of the slot base insulation
The free winding ends of the individual wire strands of the winding mat must be contacted in accordance with a wiring diagram and the phase connection terminals discharged from the coil end.

Interconnection elements are mounted to enable the contacting of two non-adjacent copper ends and thus the connection between winding sets.

Contacting is usually achieved by a material-to-material joining method, such as a welding process.

The interconnection concept and the interconnection elements have a significant influence on the automation capability of this process.

### Alternative technologies [excerpt]
- Laser welding
- Resistance soldering/resistance welding
- Mechanical processes (e.g. hot crimping)
- Electron beam welding

### Quality features [excerpt]
- Low splash and pore formation
- Electrical conductivity of the weld
- Tensile strength of the weld
- Low thermal input
- Weld geometry
- Shape and position tolerances of the interconnections

### Quality impacts [excerpt]
- Energy input, laser power, wavelength
- Focus
- Welding preparation (stripping, surface cleaning, etc.)
- Material selection (alloy percentage)
- Position/location of the connectors (welding gap)
Impregnate Stator

Process Description

• To improve heat dissipation from the stator, to mechanically fix the winding and to provide an additional layer of electrical insulation, the stator is impregnated with an epoxy resin.
• The stator and the resin are heated before application.
• The impregnating resin is applied to the preheated coil end.
• Slot penetration takes place according to the principle of the capillary effect.
• To ensure uniform distribution of the resin within the stator, the stator including the pick-up rolls continuously.
• Gelation, 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 radiation (UV radiation)
• Additionally: weight control before and after the process to determine the resin uptake as well as camera monitoring for application control

Quality features [excerpt]

• High fill factor (particularly in the slot)
• Avoidance of unfilled cavities
• High thermal conductivity
• Little rework required for cleaning
• Aging resistance
• Freedom from damage of the lamination stacks

Quality impacts [excerpt]

• Process temperature profile
• Application quantity of the resin
• Resin temperature profile
• Rotation speed
• Continuity/synchronization of the rotation
• Slot geometry
Stator Test

Process Description

- The last process step is the electrical testing of the stators. Individual electrical tests can also be carried out at an earlier stage in order to identify rejects at an early stage.
- Among other things, the stator test checks:
  - Insulation strength
    - Quality-relevant: internal isolation between turns within/different phase(s)
    - Safety-relevant: external insulation between the conductor system and the lamination stack
  - Resistance: testing of the ohmic resistances within the conduction system
  - Others: polarization index test, step voltage test, rotation direction test

Further Information

Possible testing technologies [excerpt]

- High voltage test AC: high AC voltage and automatic fast shutdown when a limit current is exceeded
  - Test method for determination of insulation resistance, detection of ground and phase faults as well as partial discharges
  - Alternative: high voltage test DC with 1.5 times the test voltage
- Surge voltage test: surge pulse and discharge of the stored energy into the inductance
  - Test method for the detection of winding faults, insulation faults, and partial discharges

Quality features [excerpt]

- Symmetry of the phase resistances
- Insulation strength winding/winding and winding/housing
- Freedom from partial discharge of the entire system

Quality impacts [excerpt]

- Insufficient contacting
- Test parameter settings
- Damage to the insulation systems
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.

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