PRODUCTION PROCESS OF A HAIRPIN STATOR

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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

Available online

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.

1st edition
ISBN 978-3-947920-35-8
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Available online

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

Available online
Hairpin Technology

In comparison to other winding technologies

- In hairpin technology, solid copper wires (usually copper flat wires) are inserted into the stator slots of the lamination stack.
- Similar to conventional stators, the lamination stack consists of a large number of electrical sheet layers insulated from each other (sheet thickness: approximately 0.18 mm to 0.5 mm).
- The I- or U-shaped bent hairpins (see illustration) thus replace the classic winding methods such as needle winding, flyer winding, and the flyer retraction technique.
- Hairpin technology originated in generator construction and, together with wave winding ("continuous hairpin"), has been increasingly establishing itself for use in electric traction drives for several years.
- Hairpin technology is suitable for the stator winding of both synchronous and induction motors.
- With hairpin technology, a mechanical slot filling factor of up to 90% can be achieved (electrical: up to 70%).
- In the automotive industry, usual output quantities of a hairpin stator production are between 150,000 and 200,000 units per year and line.

Design and Components of a hairpin stator
Potential of the hairpin stator technology

From a product perspective
• Large conductor cross section enables high currents and thus high-torque motors
• Rectangular conductor cross sections increase the electrical fill factor in the stator slot compared to round conductor cross sections
• Complex winding schemes possible
• Comparatively low winding head height on the closed side of the hairpin

From a production perspective
• Deterministic forming and assembly processes replace stochastic winding processes
• High automation capability and scalability
• High process stability and repeatability
• High cost efficiency in series production

Process Chain of hairpin stator production

1. Straighten copper wire
2. Strip copper wire
3. Cut copper wire to length
4. Bend copper wire
5. Insulate stator slots
6. Pre-assemble hairpins to basket
7. Join hairpin basket
8. Widening
9. Twisting
10. Cutting to length (optional)
11. Crown welding
12. Welding interconnections
13. Insulate copper ends
14. Impregnate stator
15. Stator test
Straighten Copper Wire

Process Description

- The enameled copper wire is supplied on a copper wire coil.
- Due to the copper wire being wound onto the coil, the respective curvatures in the wire structure 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.
- Exact straightening of the rectangular copper wire leads to an increase in positioning accuracy during assembly, joining, 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 should be controlled continuously and adapted, if necessary.

Further Information

Alternative technologies [excerpt]

- Stretch leveling
- 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]

- Position of straightening rolls
- Material springback and yield point
- Wire feed speed/continuity
- Directional material handling
- Residual stress
- Tool stiffness
Strip Copper Wire

Process Description

• For the downstream welding of the copper ends (process step 11), these must be partially stripped.
• In laser-based stripping, the area to be stripped is processed several times by laser (or several lasers with different wavelengths) in pulsed mode.
• Initially, the insulation “burns” with a visible flame as the conductor and insulating material are heated by the laser.
• After removing most of the insulation, the laser radiation is absorbed by the base material.
• Abrupt thermal heating of the conductor “blasts off” any remaining insulation and combustion residues.

Further Information

Alternative technologies [excerpt]
• Mechanical methods
  • Grinding
  • Scraping
  • Milling (see next page)

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]
• Beam source/wavelength
• Process speed (feed rate)
• Laser power
• Pulse duration
• Feed
• Insulation material
Strip Copper Wire

Process Description

- For the downstream contacting of the copper ends (process step 11), these must be partially stripped.
- 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 even 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 processes (see previous page)
- Mechanical methods
  - Grinding
  - Scraping

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/RPM
- Feed rate
- Wear on the cutting edges
- Wire guidance and oscillation
- Direction of rotation
- Conductor and insulation material
Cut Copper Wire to Length

Process Description

- The straightened copper wire is cut to length according to the required hairpin geometry.
- 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.
- Optional: process-integrated sharpening/beveling of the copper ends for easier installation of the hairpins in the stator lamination stack.

Further Information

Alternative technologies [excerpt]
- Shear cutting
- Knife cutting
- Bite cutting
- Tearing
- Tear-in

Quality features [excerpt]
- Position tolerance (positioning of the cut)
- Shape tolerance of the bevel
- Cutting burr
- No damage to the conductor insulation
- No deformation of the wire cross section

Quality impacts [excerpt]
- Product properties
- Clamping force
- Cutting gap in relation to material thickness
- Wear of cutting tools
- Cutting speed
Bend Copper Wire

Process Description

• The copper wire is bent into the three-dimensional, so-called hairpin geometry.
• A distinction is made between 2D and 3D bends.
• The bending process can be integrated (CNC-controlled, 2D and 3D bending in one process) or multi-stage (2D and 3D bending consecutively).
• The copper wires are bent three-dimensionally in order to be able to connect different layers with each other in the stator.

Further Information

Alternative technologies* [excerpt]

• CNC-bending: computerized control of the bending machines
• Swivel bending: The workpiece is clamped between the upper and lower beam of the bending tool.
• Die bending: The pre-bent workpiece is placed on a die with a V-shaped opening.
• Free bending: The geometry to be created is controlled by the movement of the tool holder.

Quality features [excerpt]

• Form, angle and position tolerances (absolute position/twist, opening angle)
• No insulation damage or change of insulation thickness at the outer radius
• Cross-section change/residual stress condition
• Repeatability (result dispersion)

Quality impacts [excerpt]

• Forming time, speed and force
• Punch radius (depending on geometry)
• Forming force (especially bending force)
• Springback behavior of the wire
• Semi-finished product properties (e.g. E-modulus, yield point)
• Quality and wear of the bending tool

*Technology alternatives are shown and described in more detail on the following page.
CNC bending (2D and 3D)
- Integrated 2D and 3D bending process
- Copper wire is bent directly into the desired position by a single bending tool or multiple ones
- Flexible process for manufacturing different hairpin geometries on one line
- Comparatively high cycle time

Swivel bending (2D)
- Positioning of the wire
- Upper beam clamps the copper wire against the lower beam
- Bending bars give the copper wire the required 2D geometry.
- Use in combination with die bending or “free bending” (3D bending operations)

Die bending (3D)
- Positioning of the wire in the bending die
- Downward movement of the stamp gives the hairpin a 3D contour
- High reproducibility with short cycle time
- Use in combination with swivel bending, among other things

Free bending (3D)
- One leg of the 2D-shaped hairpin is positioned between the upper and the lower cheek.
- Gripper takes free hairpin leg and pulls hairpin apart
- Use in combination with swivel bending, among other things
Insulate Stator Slots

**Process Description**

- The stripped hairpins are separated from the ground potential of the lamination stack by using slot insulation paper.
- Cutting and folding (slot base and slot opening folding) of the insulation paper is possible both manually and fully automatically.
- Constant synchronization of the material feed, the timing of the insertion, the forming force and kinematics during the forming and lining of the slots is required.
- Optionally, the slot paper can be solidified in the stator slots, and the slot paper projection can be flared in a funnel shape for easier assembly.
- The inspection for damage as well as freedom from wrinkles is done manually or automatically.

**Further Information**

**Alternative technologies [excerpt]**

- Plastic injection molding: insulation of the slots
- Powder insulation: application of powder resins or varnishes and subsequent curing
- No slot insulation (higher requirements for other insulation systems)

**Quality features [excerpt]**

- Shape and position deviation of insulation
- No damage at axial end edge of the stator lamination stack
- Freedom from cracks and wrinkles
- Air pockets (slot insulation/stator lamination stack)
- Defined paper overlap

**Quality impacts [excerpt]**

- Stator geometry (slot geometry and length)
- Folding scheme
- Lining and winding process
- Insertion speed
- Forming force
Pre-assemble Hairpins to Basket

Process Description

- Undercuts and overlaps of the winding head geometry limit the sequential direct assembly of the hairpins into the lamination stack and require pre-assembly outside the stator.
- The hairpins are pre-assembled outside the lamination stack to form a hairpin basket or several hairpin baskets.
- The basket is assembled in a workpiece carrier or in a transfer device.
- Pre-assembly strategies such as screwing in, radial infeed and repositioning are used.
- During pre-assembly, ensure that the hairpins are correctly sorted (approximately three to 16 types per stator).
- The high dependence of pre-assembly on the winding scheme and hairpin geometry requires complex special machine construction and limits variant flexibility.

Further Information

Alternative technologies [excerpt]
- Direct mounting

Quality features [excerpt]
- No damage to the conductor insulation
- No plastic deformation of the hairpins
- Shape and position accuracy of the pre-assembled basket

Quality impacts [excerpt]
- Handling and clamping forces
- Surface of the parts in contact with the component
- Hairpin geometry deviations
- Undercuts and overlaps
Join Hairpin Basket

Process Description

• The hairpin baskets are transferred from the pre-assembly station by multiple gripping systems and inserted axially into the lamination stack (joint gap: usually <0.1 mm).
• The final alignment of the hairpins takes place in the gripping system or by means of additional assembly fixtures.
• During the assembly process, the slot insulation must be ensured against damage and slipping.
• Draft angles on the hairpins and/or fixtures facilitate insertion into the stator slots.
• If necessary, hairpin special shapes can be inserted individually into the stator lamination stack to reduce the amount of interconnection required in the subsequent process steps.
• Finally, the hairpins are aligned in the axial end position (for example, by using a plate).

Further Information

Alternative technologies [excerpt]

• Direct mounting

Quality features [excerpt]

• No damage to the conductor insulation
• No damage and dislocation of the slot insulation
• No plastic deformation of the hairpins
• Shape and position accuracy of the winding head and the free copper ends

Quality impacts [excerpt]

• Slot geometry and joint gap
• Joining direction
• Joining force
• Hairpin geometry deviations
• Handling and clamping forces
• Surface of parts in contact with the component
Widening

Process Description

- The copper ends are radially exposed and separated for axial accessibility of the twisting tool.
- Supporting the copper ends above the slot insulation is necessary to ensure a defined forming process on the twisting side.
- The copper ends are radially formed by a forming tool to produce sufficient distance from each other.
- The process can be carried out slot-wise, layer-wise, or in one step, which has an influence on the achievable cycle time and variant flexibility.

Further Information

Alternative technologies [excerpt]

- Axial wedge-shaped forming tool for single or grouped copper ends
- 3D-printed winding head

Quality features [excerpt]

- Shape and position tolerances of the copper ends
- No damage to the conductor insulation
- No damage to the slot insulation
- Height tolerance

Quality impacts [excerpt]

- Mechanical properties
- Orientation of the copper ends before the process step
- Wire cross section
- Surfaces of parts in contact with components
Twisting

Process Description

- The copper ends are tangentially formed in layers and brought into their final shape, with the aim of aligning the copper ends to be contacted parallel to each other.
- The copper ends are formed by a rotational tool movement. (The tool has to follow translationally.)
- Free wire ends are supported in the bending radius during the twisting process.
- If necessary, support elements are used on the opposite winding head to counteract the axial lifting force of the twisting process.
- Twisting tools are manufactured individually, depending on the stator geometry, which results in high tool costs and limited variant flexibility.

Further Information

Alternative technologies [excerpt]

- Prefabricated connecting ring (twisting process not required)
- 3D-printed winding head (twisting process not required)

Quality features [excerpt]

- Shape and position tolerances of the copper ends
- No damage to the conductor insulation
- No damage to the slot insulation
- Height tolerance

Quality impacts [excerpt]

- Mechanical properties
- Orientation of the copper ends before twisting
- Wire cross section
- Surfaces of parts in contact with components
Cutting to Length (optional)

Process Description

• To compensate for height differences of copper ends to be contacted with each other, they are adjusted with the help of a cutting device (usually shear cutting).
• A positioning element is used during the process to fix and protect the copper ends, which can be used for repositioning.
• Leaving copper sections in the winding head has to be avoided (risk of short circuit).
• The process can be performed individually, slot-wise or in full cut, which has an influence on the achievable cycle time and variant flexibility.
• The cutting process can be skipped if the upstream processes are managed with reliable tolerances.

Further Information

Alternative technologies [excerpt]

• Mechanical (grinding, cutting)
• System for tolerance compensation

Quality features [excerpt]

• No material residues in winding head or stator
• No impurities at the copper ends
• Shape and position tolerances
• No damage to the insulation
• Burr as small as possible

Quality impacts [excerpt]

• Mechanical properties
• Tool wear
• Cutting speed
• Surfaces of parts in contact with components
• Winding head complexity
Crown Welding

Process Description

• According to the established winding scheme, the copper ends are electrically contacted.
• Before the welding process, a camera-based sensor system with integrated control should also be used to detect the position of the copper ends.
• Adjacent copper ends are fixed by means of a clamping device (goal: zero gap formation).
• Absorption of the laser power melts the surfaces of the copper ends. After the subsequent cooling process, they are bonded together.
• Depending on the winding head geometry, subsequent galvanic isolation of adjacent welded joints may be necessary to prevent electrical short circuits.
• The optimum welding strategy must be selected depending on the materials used and the stator design.

Further Information

Alternative technologies [excerpt]

• Electron-beam welding
• Resistance soldering/resistance welding

Quality features [excerpt]

• Low splash and pore formation
• Electrical conductivity of the weld
• Tensile strength of the weld
• Low thermal input
• Weld geometry (height of the weld)
• Homogeneous weld cross section

Quality impacts [excerpt]

• Energy input, laser power, wavelength
• Focus
• Welding preparation (stripping, surface cleaning, etc.)
• Product properties (alloy content)
• Copper end position/location (weld gap)
Welding Interconnections

Process Description

- In this process step, the term “interconnection elements” refers to the contact ring including jumpers, terminal connectors, and star connectors.
- First, the interconnection elements are mounted to enable the contacting of two non-adjacent copper ends and thus the connection between sets of winding sets.
- The interconnection concept and the interconnection elements have a significant influence on the suitability for automation of this process.
- Absorption of the laser power melts the surfaces of the copper ends and the interconnection elements. After the subsequent cooling process, they are joined with each other.

Further Information

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 (height of the weld)
- Geometry tolerance of the interconnections

Quality impacts [excerpt]
- Energy input, laser power, wavelength
- Focus
- Welding preparation (stripping, surface cleaning, etc.)
- Product properties (alloy)
- ConnectorPosition/location (weld gap)
After the welding process, the stripped, welded copper ends must be coated again. Often the whirl sintering process is used, applying a powder coating. After preheating the copper ends, they are immersed in the sintering basin. The swirled powder melts on the copper surface as long as the surface temperature is above the melting temperature of the plastic. The coating thickness depends, among other things, on the preheating temperature, immersion time, and insulation material. After melting, cooling takes place on a run-out section.

**Further Information**

**Alternative technologies [excerpt]**
- Immersion process
- Trickle process
- Full potting

**Quality features [excerpt]**
- Layer thickness of the resin
- Dielectric strength
- No air pockets in the insulation

**Quality impacts [excerpt]**
- Relative position of the copper ends to each other
- Gap between radial layers
- Homogeneous density of grain size distribution in the sintering basin
- Process temperature profile
- Application quantity of the powder
**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 winding head.
- 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.
- 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
- Freedom from damage of 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
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.
- Following tests are carried out (excerpt):
  - Insulation strength
  - Quality-relevant: internal isolation between turns within one/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
- No partial discharge

Quality impacts [excerpt]

- Insufficient contacting
- Test parameter setting
- 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.