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Innovative Assembly of Stators using Ambidextrous Kinematics

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***Abstract*—Existing production systems for electric motors are characterized by a high degree of automation for serial production and also by intensive manual operations at low volumes. In this paper, the flexible, automated assembly of stators of electric drives, using an ambidextrous robot, is presented. The emphasis is placed on the conceptualization and simulation of the assembly processes of limp windings and flexible slot covers, the development of the corresponding product-independent tools and additives, their implementation in a demonstration mounting system, as well as an accompanying evaluation of the robot-based final assembly of stators.**

***Index Terms*—Electric Motor, Robot, Production, Assembly, Manufacturing, Automation**

I. Introduction

Since the invention of Barlow's wheel in 1822 [1] the number of electric motors being produced each year has continuously risen. By 2020 an annual growth rate of 6% will be reached [2]. One consequence of this development is an increasing diversity amongst electric machines and an associated complexity of the assembly processes [3]. In this context, the development of innovative process technologies is an important condition for obtaining a competitive advantage. When manufacturing prototypes and small series, universal standard kinematics offer the advantage of flexible production (e.g. winding different stator types [4]). Within this paper, a robot-based stator assembly process chain, which was developed at the E|Drive-Center of the Friedrich-Alexander-Universitaet Erlangen-Nuernberg, is presented and classified. The focus will be set on the winding- and slot-cover assembly process.

II. Robot-based stator assembly

The process chain of the robot-based stator assembly starts with the winding and assembly of the single coils.

The following process steps are pre-pressing, impregnation and the cover plate insertion process. The chain is finished by the processes of interconnection, bandaging and final pressing [5]. [6]

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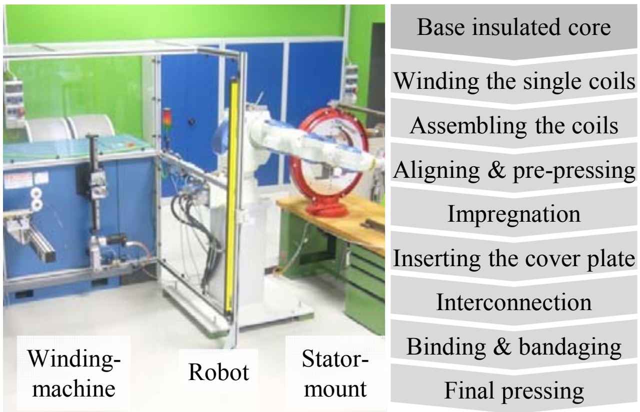

Fig 1 Process Chain of the robot-based assembly of stators

To assemble the stator, a demonstration cell including a risomat linear winding machine, a yaskawa dual-arm robot and a stator mount tool has been set up (Fig 1, left). All tools and machines have been constructed to produce stator sizes from 112 millimeters up to 250 millimeters [7].

III. Flexible winding assembly

There are different challenges in the robot-based assembly of windings. On the one hand, it is difficult to handle flexible parts such as coils. The assembly`s tasks are the reliable gripping, fixation and manipulation of the winding. On the other hand, the winding should not be damaged during the process (insulating and clamping the wire). [8]

One important prerequisite for all processes is a defined stator position. This is fulfilled by developing a stator mount that is accessible from both sides and allows a centered holding and defined radial movement of the fixed stator.

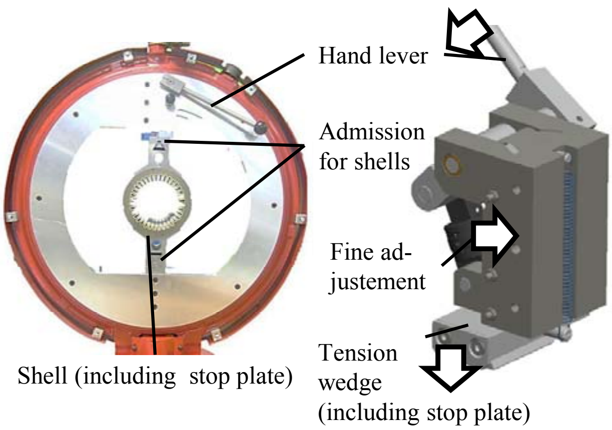

Fig 2 Centering stator holder

The fast and precise setup of the stator is achieved by means of a hand level, which pushes a stator specific shell

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on the surface of the lamination core. The alignment of the stator is done by stop plates on the shells (axial) and a v-shaped fitting key (radial) [8]. The stator can be automatically moved radially by an integrated servo motor, which allows for exact positioning.

In the following sections, the winding and the assembly of the single coils will be described.

A. Winding the single coils

Typically, universal winding stencils are used to manufacture the single coils, but in the case of robot-based automation it is not possible to reach the wire. As a consequence, a stator specific stencil was developed (Fig 3). The different chambers, formed by flat bars, are accessible for robotguided tools. Other properties are the short setup times and being able to different stator lengths through the adaptable gap between the symmetric stencil halves.

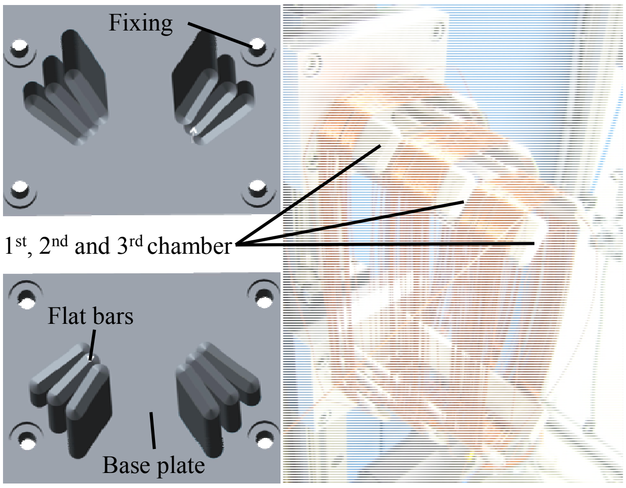

Fig 3 Stator specific winding stencil

The two different methods for assembling the single coils - a draw-in process or a combined inserting / pull-in process - will now be presented. [9]

B. Insertion of the single coils

In Fig 4, the concept of and the tools for the setting-in process are shown.

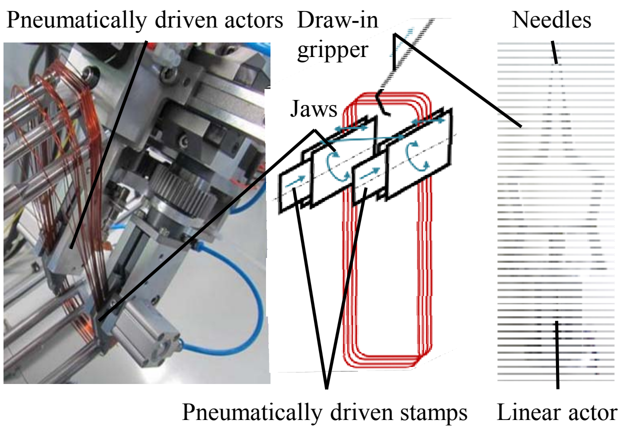

Fig 4 Concept of the combined insert- / draw-in process, using an insert gripper (left) and draw-in gripper (right).

The insert gripper (left) is attached to the first robot arm and has three different tasks: picking up the winding from the stencil, transferring it, and inserting the winding into the slots on the left side of the stator.

The draw-in gripper is attached to the second arm of the robot and captures the windings to pull them to the right side of the stator. During this movement, the coils are drawn into the slots. The grippers are flexible with regards to different stator types. To adapt to different geometries, the actors can adjust the rotation and the distance of the jaws. The pneumatic actors fulfill the tasks of gripping and pushing the single coils.

C. Drawing in the single coils

Within the draw-in process, the first robot arm picks up three coils with the attached tool. Affixing the single coils is accomplished in a force- and positive locking way by two pneumatic grippers, consisting of three parallel jaws. The windings are transferred onto the needles of the draw-in tool, which is manipulated by the second robot arm and placed in the stator. After having been equipped, the draw-in tool is pushed through the stator by the draw-in head and the windings are pulled into the slots. Thereafter, the stator rotates and the tools can be repositioned.

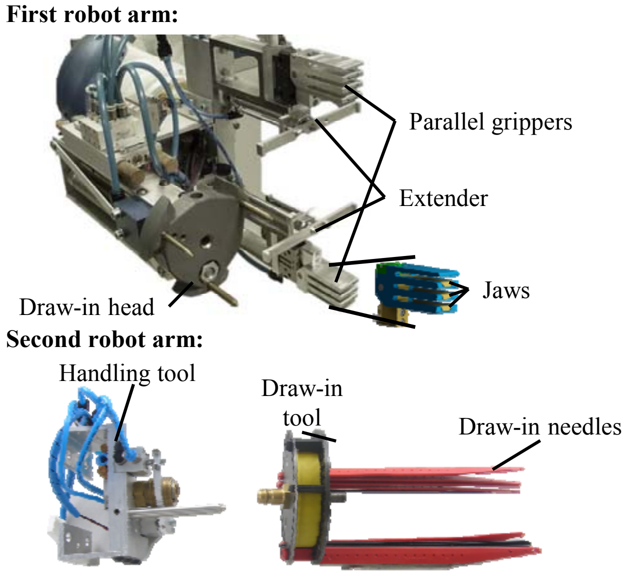

Fig 5 Draw-in tool

IV. AUTOMATED ASSEMBLY OF SLOT COVERS

The next step in the process chain is the assembly of the slot covers. The purpose of these components is both the electrical insulation and the mechanical fixation of the coils. The greatest challenge behind assembling the slot covers is the limited accessibility to the slots, caused by protruding wires and the winding head. Therefore, a robot-based tool must integrate solutions to push the wire into the target position. In the following sections, the implementation of a continuously fed cover plate assembly process and the substitution thereof will be described.

A. Assembly of slot covers

There are various possibilities for a robot-based assembly of cover plates (e.g. draw-in process, punch & dies principle) [10].

The prepared tool, shown in Fig 6, is based on two feeding rolls, which are pressed together by compression springs with forces from 250 N – 400 N (depending on the draw-in force).

The assembly sequence starts by approaching the stator at an angle of about 60° to bypass the winding head with a subsequent horizontal descent to push down protruding wires.

The unworked material is driven and formed by the rolls and guided into the slots through a tunnel, which integrates a cutter that cuts the covers to the statorspecific length, and an applicator that has an additional functional surface to bank the incomplete cover. [10]

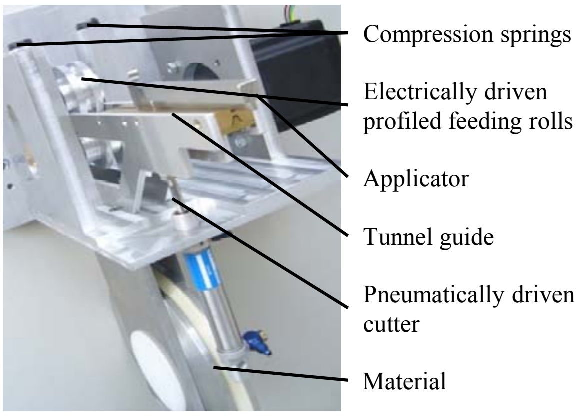

Fig 6 Robot-based tool for assembling cover plates

B. *Substituting the assembly of slot covers*

In light of the aforementioned problems of being able to access the slots, other methods for robot-based isolation are more reliable. Fig 7 shows a tool used to obviate the need for assembling the cover plates. The basic idea is to dose an adhesive material with the same mechanical and isolating properties (e.g. dielectric and mechanical strength, thermal conductivity, thermal class F) as above. After material experiments [11], a modified polyurethane resin was selected to be deposited by a squeeze valve.

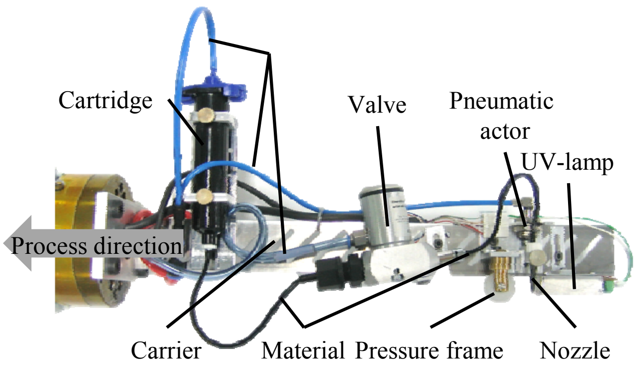

Fig 7 Robot-based tool for substituting the cover slides

The process starts with the introduction of the pressure frame in the slots to backpress protruding wires. The nozzle is manipulated into working position by a pneumatic actor and the material is provided by the squeeze valve. A UV-lamp is activated during the dosing to start the curing immediately.

The size of the cartridge is adapted to the stator size and can be also replaced by a pressure tank if necessary. All components are installed on an aluminum carrier, which makes the tool very compact and suitable for small stator diameters. The carrier also allows duplicating the components to integrate the impregnation process.

Preliminary experiments with an unsaturated polyester resin have demonstrated the basic effectiveness.

V. Further Processes

Upon insulating the winding, the subsequent processing steps are the interconnection and the pressing of the winding head. The developed robot-based tools are shown in the following sections of this paper.

A. *Interconnection of the winding ends*

The most important condition for a reliable interconnection is correct wiring. The position of the free wire ends is known until the pick-up process of the single coils from the stencils. To maintain this information, the wire ends must also be gripped, handled and placed. Fig 8 shows the developed tools: The gripper (right) is attached to the winding gripper (shown in Fig. 5) and integrates two parallel grippers or picks up the wire ends and a cutter to slice the wire of the stencil.

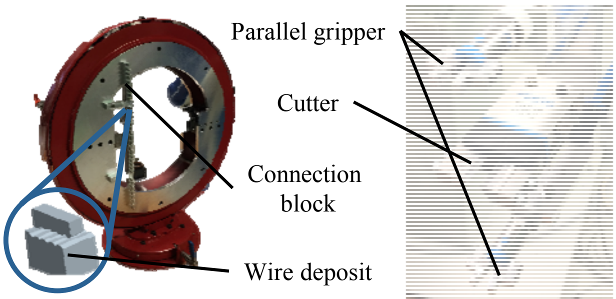

Fig 8 Handling the wire ends: deposit (left) and gripper (right)

The wire ends are placed at the deposit, attached to the stator mount, and the information is saved in the robot program.

The subsequent welding process starts with the collection of the wires according to the wiring diagram and can be executed in two different ways. In the first approach, a combined collection- and press welding tool is adapted to the robot (Fig 9). The wire ends are collected in hook-formed welding surfaces, pressed together and electrically melted. However, the high emerging currents and forces induce safety measures in order to prevent coupling to the robot.

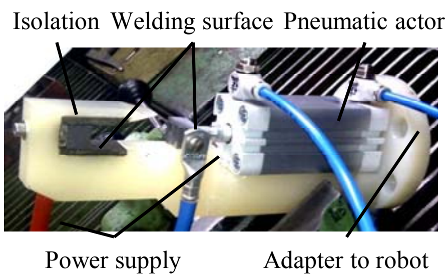

Fig 9 Robot-based welding of the wire ends

In the second approach, the robot only picks up the wire ends and transfers them to a hot crimping machine. However, in this case the wire conductors are longer in order to bypass the space between the stator mount and

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other machinery.

B. Concept of robot-based pressing

Depending on the size, there are varying presses for forming the winding head. The primary idea behind a robot guided tool (Fig 10, left) corresponds to a conventional process:

Two rams are pushed together and an integrated mandrel stretches the coils. Implementation is accomplished by a divided tool.

The first half of the tool is attached to the robot, and the second half is fixed at the assembly cell to absorb the pressing forces. Both halves are guided to the stator (robot / robot and profile rail), which is still fixed on the mount and is closed by a rotational movement of the robot guided half.

The actor (pneumatically) drives the ram to the side of the stator. The resulting axial tension compresses the springs, which induces a radial movement of the dies through transferring the forces by means of sloping surfaces (Fig 10, right).

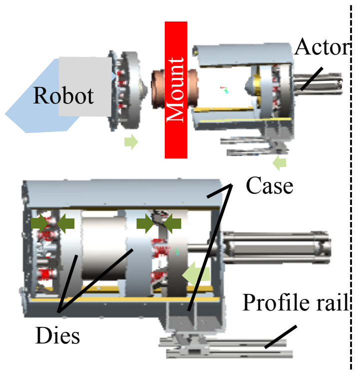

Fig 10 Robot-based pressing tool

VI. Classification of a Robot Based Stator Assembly System

To prove the sustainability of the tools and processes shown, the assembly system was evaluated. The focus was placed on economical efficiency and based on MTM analyses of various automated production systems. [8]

A distinction must be drawn between different scenarios and the scaling of the systems to a specific output. In the case of scaling, all production lines must be scaled to the automated variant (50,000 pieces / year). Naturally, in this quantity all advantages of the automation have come to gear.

On the other hand, it is possible to define specific scenarios in which the alternative production systems work most efficiently in an economical sense. Fig 11 shows the piece costs of manual, partly automated, robot-based automated and automated assembly systems.

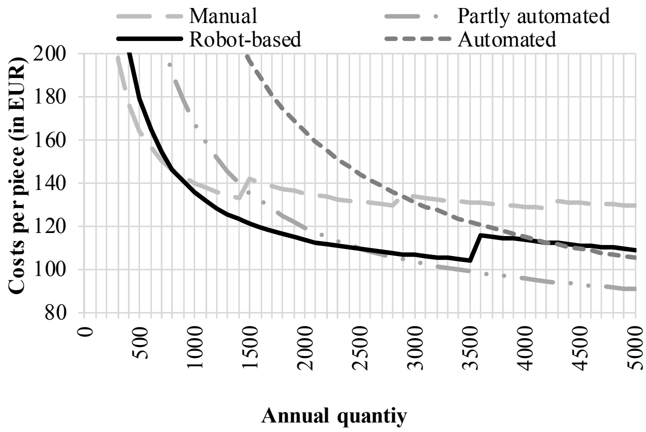

Fig 11 Cost per piece of varying assembly systems

In the case at hand of the assembly of stator sizes from 112 millimeters up to 250 millimeters, the robot-based system is the most economical variant for annual quantities between 820 and 2580 stators.

VII. Conclusion and Outlook

Continuous development and globalization generates the need for innovative and flexible production technologies for electric drives. In this paper, tools and processes for a robot-based assembly of stators have been presented which allow a more efficient manufacturing of customer specific electric motors.

Further developing the processes to specific motors and technologies (e.g. bonding), as well as integrating a CAD / CAM chain, are the next steps in the industrialization of the demonstrated cell.

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