Robot-based Production of Electric Motors with Hairpin Winding Technology

Alexander Kuehl, Andreas Riedel, Alexander Vogel, Sebastian Hartl, Tobias Glaessel,
Michael Masuch, Joerg Franke

***Abstract*— In the context of the megatrend electro mobility, electric drives are being given a massive innovation boost by their use in the automotive drive train. The associated demand for an increase in power density and the necessity to reduce costs in series production will improve the winding of electric machines and the associated production processes. Bar wound windings represent a promising alternative with numerous advantages. In the special case of hairpin motors, the winding consists of a large number of preformed elements made of painted copper wire that have to be assembled and connected to each other. In contrast to the previous production chain, flat wires are first pre-bent, then inserted and finally the ends get twisted.**

The following article explains the motivation for the use of bar windings and the corresponding production chain. A particular focus is on energy-efficient production flexibility in the ramp-up phase through the use of universal kinematics. The described processes have been realized at the E|Drive-Center at the Institute for Factory Automation and Production Systems (FAPS) of the Friedrich-Alexander-University Erlangen-Nuremberg (FAU).

***Index Terms*— electric motor; hairpin; manufacturing; robot; electric drives production**

I. INTRODUCTION

In contrast to conventional winding processes, techniques with plug-in coils - which also include the hairpin process - can usually only be automated with additional effort but offer numerous advantages such as the feasibility of higher copper filling factors which leads to a higher degree of efficiency with a smaller installation space.[1].

However, the degree of automatability of the hairpin process is very high, so that greater investment costs can be amortized. There are also limitations in the sizes that can be realized for stators of electric motor. Medium to large sizes from about 100 mm diameter are possible. Compared to conventional winding processes, medium cycle times can be achieved. Otherwise, the winding pattern for techniques with plug-in coils is unsurpassed. A layer winding is formed with a very high groove-filling factor and an orderly winding head. This results in good electrical properties of the electric motor. In summary, it can be noted that every winding process has its purpose and the best winding process must be selected from case to case. [2]

Within this paper flexible automated concepts and processes as well as tool concepts, which has been developed at the E|Drive-Center at the Institute FAPS from Friedrich-Alexander University Erlangen-Nuremberg (FAU) will be shown. The flexibility to be researched should, in particular, enable the energy-efficient and individual automated assembly of motors, which represent high challenges for many sites. This paper concentrates on the process steps hairpin forming and assembly.

II. PRODUCTION OF STATORS OF ELECTRIC MOTORS WITH HAIRPIN WINDINGS

The procedure for equipping stators with hairpin coils is still very new, which is why relatively few fully automatic solutions exist on the market.

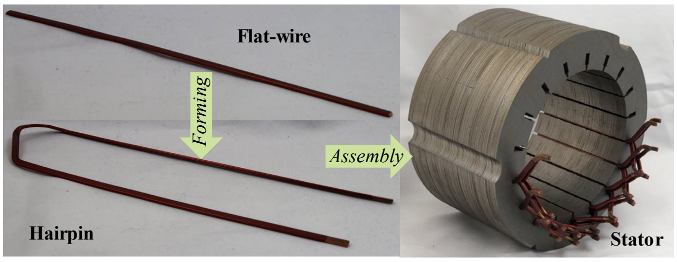

Fig. 1. Flatwire, Hairpin and Stator

In general, the process is divided into the following steps, also shown in Fig. 2.

A. Hairpin forming

Within the initial step (hairpin forming), the hairpin is bent from insulated enameled copper flat-wire. This can be realized either using templates (like described in [3]) or by robot-controlled bending of the plug-in coils, as shown in Fig. 3.

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A. K. is heading the E|Drive-Center at the institute FAPS, Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Nuremberg, 90429 Germany, (e-mail: alexander.kuehl@fau.de).

A. R. is research associate at the institute FAPS, Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Nuremberg, 90429 Germany, (e-mail: andreas.riedel@faps.fau.de).

A.V. and S.H. wrote the master thesis at the at the institute FAPS, Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Nuremberg, 90429 Germany

T. G. is research associate at the institute FAPS, Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Nuremberg, 90429 Germany, (e-mail: tobias.glaesel@faps.fau.de).

M. M. is research associate at the institute FAPS, Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Nuremberg, 90429 Germany, (e-mail: michael.masuch@faps.fau.de).

J. F. Prof. and head of the institute for factory automation and production systems (FAPS), Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU), Erlangen, 91058 Germany (phone: +49-9131-85-27971; fax: +49-9131-302528; e-mail: franke@faps.uni-erlangen.de).

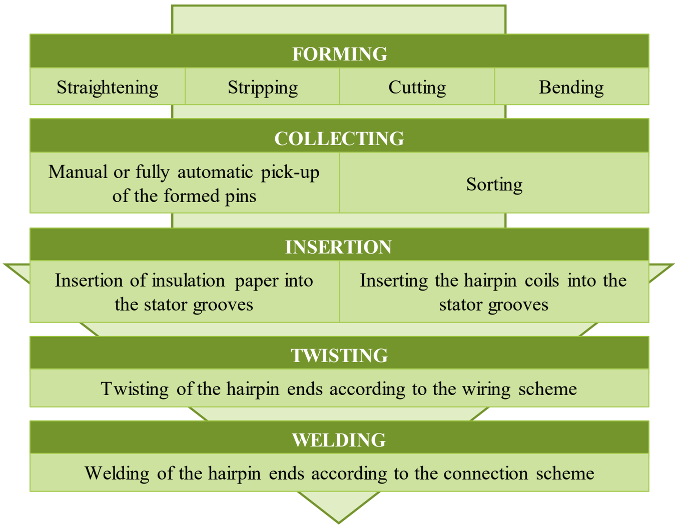

Fig. 2. Process steps for manufacturing a hairpin stator (see also [4])

In the first step, the enameled copper wire is conveyed via the wire guide to a nozzle. Here one end is stripped and then straightened with the help of the nozzle. The wire is transported via the wire guide, while a robot-controlled tool forms the coil head of the hairpin. The wire continues to be fed constantly throughout the process. Once the winding head has been formed, the next step is to bring the hairpin to the desired length, strip it at the end analogous to the other end and then cut it off. If necessary, an insertion tip can also be formed to simplify the process step of hairpin insertion.

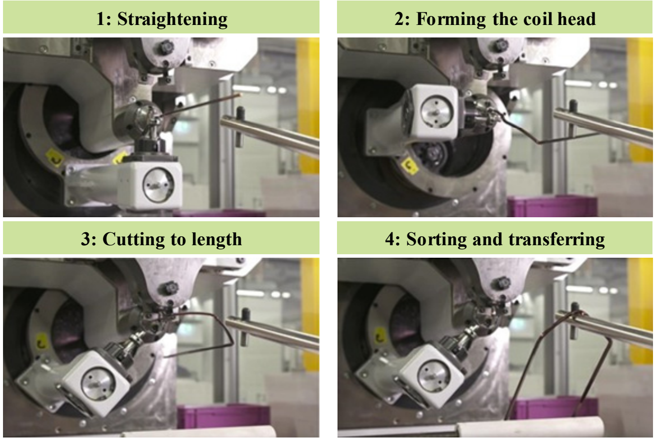

Fig. 3. Bending of flat wires to a hairpin, own presentation based on [5]

B. *Hairpin assembly*

For assembly, the individual hairpins are first ordered in the respective arrangement of the layer structure. This is especially difficult, because different forms of hairpins have to be arranged in layers. As an incorrect arrangement of the half-shaped coils has fatal effects on the functionality of the electrical machine, the zero-error principle exists in this process. Since the manual arrangement of the different hairpins is time-consuming and can only be realized with strict process controls, the aim is to develop machine-guided processes with a high degree of automation. Due to better accessibility, the innermost layer is usually built up first and the outermost layer last. A distinction can also be made as to whether the wires are arranged directly in the stator grooves and connected directly or the arrangement is carried out with the aid of a joining and assembly tool. In addition to the large number of different hairpins, the mechanical arrangement also has the difficulty that the tolerances for the arrangement and subsequent joining are very small due to the most efficient use of space. In principle, it should be noted that the use of as many identical parts as possible can considerably simplify the assembly and the assembly organization.

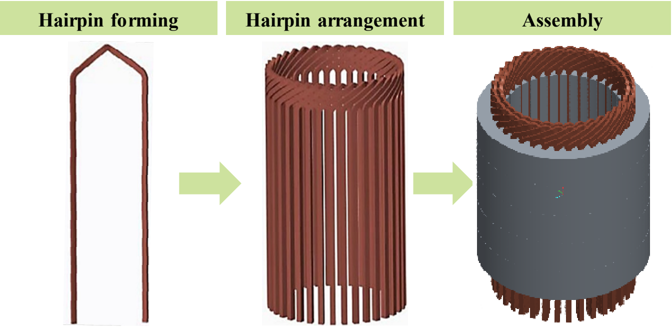

Fig. 4. Hairpin arrangement and assembly (comp: [6])

After the arrangement, the half-shaped formed coils must be inserted in the axial direction into the usually half-closed or closed stator slots. They can only be inserted into the groove with the aid of assembly and joining tools if they are arranged in the correct combination, in the desired shape and dimensional tolerances. A further difficulty is that due to the small tolerances and the additional basic groove insulation, a precise joining process must take place. Otherwise, the enameled wire or the groove base insulation can be damaged, which considerably impairs the functionality of the machine. A further goal of joining is therefore an automated process with short cycle times, which can be carried out in conjunction with the arrangement, if required. It is also recommended that the joining process is only exposed to friction between the flat wire and the groove base insulation. If the hairpins do not retain their shape, the twisted legs will cause considerable friction between the components. Another problem is that the hairpins usually gape outwards. The coils must therefore be pressed inwards to their respective diameters. A damage-free connection can only be achieved with little effort if the wires are exactly aligned with the groove.[6]

III. CONCEPTION OF THE ROBOT-BASED HAIRIN PROCESS CHAIN

The realized assembly cell is shown in Fig. 5. and consists of the components tool carrier, bending tool and assembly tool, which are placed in the middle of a dual arm kinematic robot YASKAWA Motoman SDA20 with the end effectors R1 and R2.

Withing former research work, this assembly system has already been enabled to assemble and contact round wire windings into stators with the focus of a flexible automation of the production of electric motors. [7].

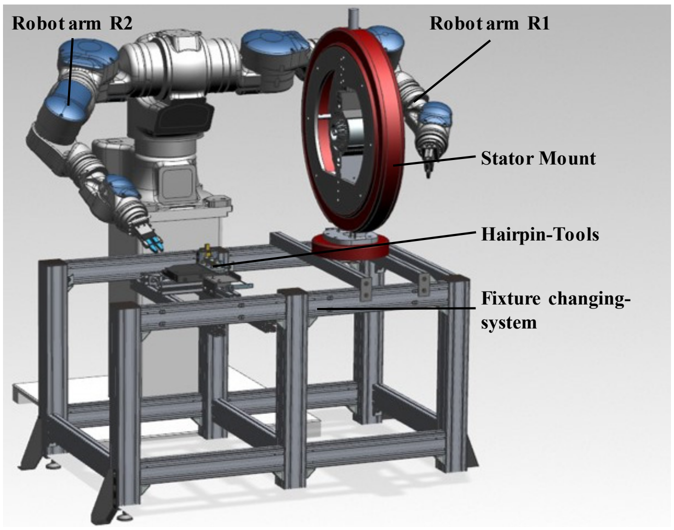

Fig. 5. Cell for the robot-based assembly of hairpin windings

A. *Fixture changing system*

The tool carrier is an aluminum scaffold, composed of strut profiles, which serves as the basic structure for all fixtures. The fixtures and tools are screwed onto modularized substructures and mounted together on the tool carrier. The table can be aligned horizontally with the help of the adjustment feet and then fixed to the ground with the angled foot plates. In this work, the bending tool and the mount for equipping the stator of an electric motor are installed on the tool carrier. In order to guarantee the position accuracy during any disassembly and the subsequent reconstruction, stop parts are attached to the strut fixture In addition, more strut profiles are mounted with metal sheets to guide the enameled copper wire.

B. *Hairpin-tools*

The bending tool is mounted directly on the tool carrier using strut profiles. The positioning is particularly important here, as the working space of the R2 robot arm can only be used to a limited extent. The simultaneous mounting of the assembly tool on the tool carrier severely limits the working space. The end effector R1 of the industrial robot cannot intervene in the process because the stator mounting of the assembly tool blocks the path.

C. *Stator mount*

The entire design of the test facility is essentially defined by the alignment of the assembly tool. This means that the two effectors R1 and R2 of the industrial robot can control the tools from both sides. The stator to be assembled can be firmly clamped with the aid of a toggle lever. The assembly tool itself essentially consists of two parts. A front part, which should help to insert the hairpin into the stator, and a rear part, which should help to twist the coils after mounting the hairpin into the stator.

IV. ROBOT-BASED FORMING OF HAIRPINS

Within the first step, the developed robot-based forming technology will be presented.

A. *Laboritory setup*

The robot-cell system is described in the chapter before. In this section the focus is set on the bending tool component.

First of all the flat-wire is straightened by passing an arrangement of rollers (see Fig. 6.). Thus guarantees an accurate final shape of the two hairpin limbs. The roller-arrangement consists of six rolls with turned outer rings and DIN 628 angular ball bearings.

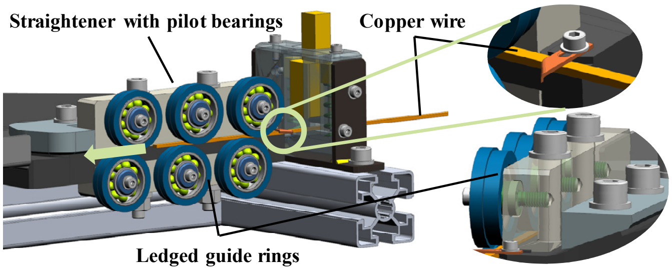

Fig. 6. Straightener with angular ball bearings

After passing the straightener, the copper coil is lead to a stop part, which is used to determine the exact length and position. This element is necessary because the industrial robot is not able to self-reliant detect the copper wire. It can only drive to the taught-in positions. Another solution can be to equip the robot with optical sensors or a computer numerical controlled wire feeder.

After the flat wire has reached the stop part, the robot can pick up the wire and the bending process starts. Therefore, the wire is bended in a slot around a mold similar to a cavity, which replicates the form of the hairpin (see Fig. 7.).

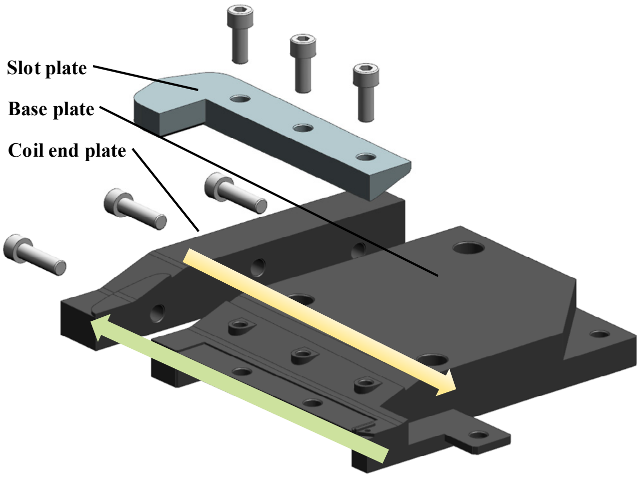

Fig. 7. Base plate with the negative form of the hairpin

The focus of the design was on avoiding undercuts, which would prevent precise demolding of the formed hairpin. For this reason, the design of the hairpin coil is without an S-shape in its coil head.

After the bending process, the formed hairpin is to be cut with a mechanical cutting tool. This tool consists of a spring-mounted cutting punch with a hardened cutting insert.

At least, the robot arm has to push the cutting punch in order to cut the copper wire.

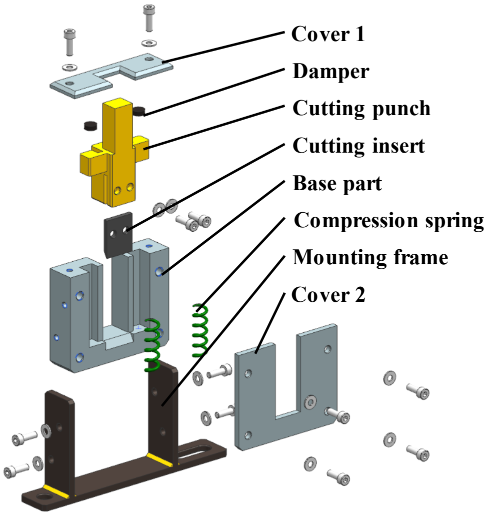

Fig. 8. Tool for cutting the flat wire

B. *Process parameters and forming experiements*

The stop position of the copper wire is at 424 mm measured from the blade of the cutting tool. Each leg of the hairpin is bent for two degrees over in order to counter the spring-back effect of the copper wire.

The programing of the robot is made by the teach-in method with a point-to-point interpolation. Therefore, each position has to be approached and saved manually by using the remote control unit of the industrial robot. The movement between the individual track points is calculated by the interpolator. This is an integrated processing unit which calculates all recorded positions in such a way that the robot axes and the tool center point (TCP) is guided precisely on this trajectory.

Before starting the robot program, the forming tool is equipped with the copper wire manually (no wire feeder equipped).

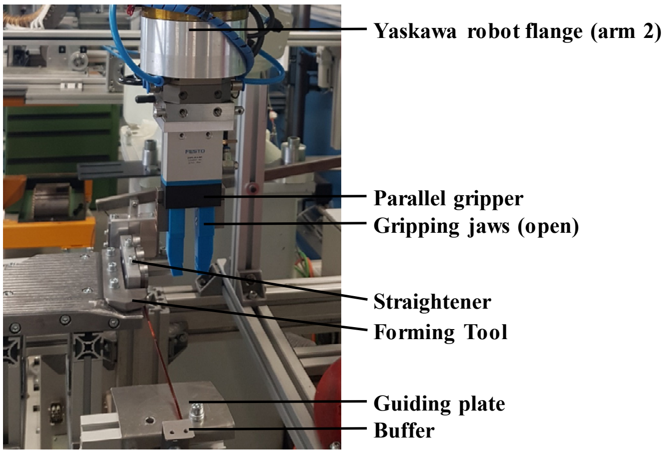

Fig. 9. Zero position of the robot manipulator R2 with opened two-finger parallel gripper

The wire is led through the pilot-heading to the stop. This is the defined start position (1) for the robot. The robot arm drives to the copper wire and grabs it (2) with its parallel gripper shown in Fig. 10.

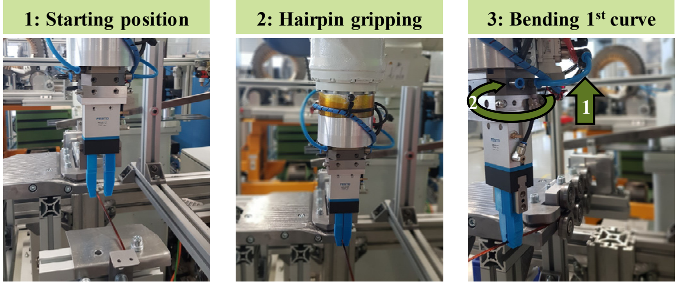

Fig. 10. Forming the first curve of the hairpin head

The robot then runs through the teached-in program. First, the parallel gripper moves in the Z direction to avoid being caught in the first bending position. (3).

The next step is a pre-bending of the hairpin head (4). This is also necessary in order to avoid being caught at the next tool corner (see Fig. 11.).

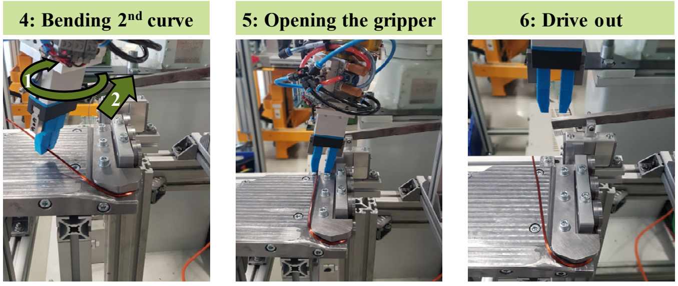

Fig. 11. Fomring of the second curve of the hairpin head

Afterwards the robot drives to the end position and the parallel gripper can detach the copper wire (5). At last, the robot manipulator leaves the working level (6) and can drive to its zero position.

C. *Demonstration results*

The experiments have shown that the tested copper wire material is much more elastic than expected. Caused by the high spring-back effect of the material, the hairpin legs are not parallel. Even applying more force by the effector in the end position, does not result in a significant reduce of this effect. Furthermore, the application of more force can lead to damages of the gripper jaws. The high spring-back effect is shown in the right side of the following Fig. 12.

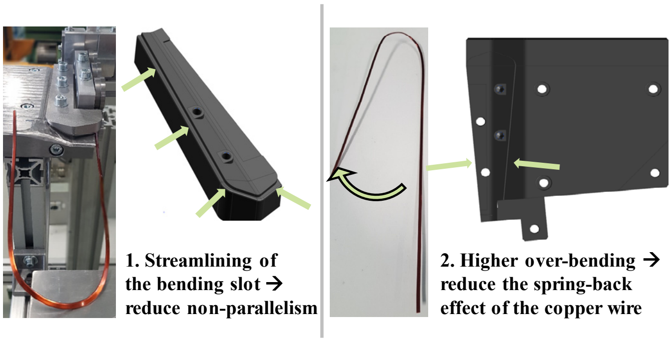

Fig. 12. Improvement of the bending tool

To get parallel hairpin legs, the hairpin has to be more over bended. Therefore, the bending slot of the tool has to be adapted as shown in the Fig. 12. In addition the copper wire entangles at sharp edges during the forming process.

As a first step, the sharp edges of the tool had to be trimmed. This led to a stable process without entangling.

In the next step, the design of the forming tool should be revised. The whole process would be more stable if the shape of the tool is much slimmer. On the one hand, this would increase the working space of the robot and on the other hand, it would reduce the amount of share edges where the copper wire be interlocked.

Due to the whole laboratory setup with the stator mount tool in the center, only one robot arm can be used for the forming, deforming, and cutting process. In addition it was not possible to cut the copper wire reliably with the cutting tool shown, since higher forces sometimes occurred during cutting than calculated. This was due in particular to the shape of the cutting insert, which was to be chamfered in a further revision.

V. ROBOT-BASED ASSEMBLY OF HAIRPINS

In the next process step the hairpins has to be assembled in the stator. Direct assembly was selected as the solution for the robot-based method.

A. Assembly concepts

Two concepts were developed for direct assembly, both of which have the same transport gripper and hairpin supply. First, the assembly of all Hairpins was considered with the help of a single assembly aid (Fig. 13. A)). Here, the shaped hairpins were to be picked up successively by the transport gripper and inserted one after the other into the assembly aid device.

As part of the second concept, a mounting aid tool was developed, which comprises only one pin and thus two grooves (Fig. 13. B)). This device moves to the next pair of grooves after each mounted pin.

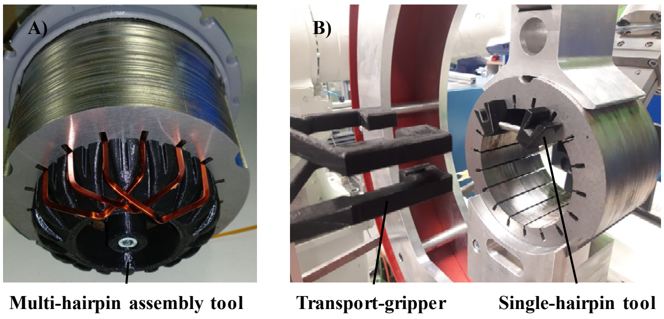

Fig. 13. Concepts A (left) and B (right) for the assembly of hairpins

Initially, concept A) was prototypically built using additive manufacturing methods and further developed in several steps. In the first assembly tests, the suitability for guided assembly of the hairpins was proven in principle, but after assembly of the entire basket, removal of the assembly device was no longer possible without destruction. The design experience could be used in the prototypical construction of concept B).

B. Laboritory setup and assemby experiments

The assembly cell (see Fig. 14.) consists of two parts. The first robot arm guides the hairpin insertion tool to the specified groove pair. The transport gripper is mounted on the second robot arm.

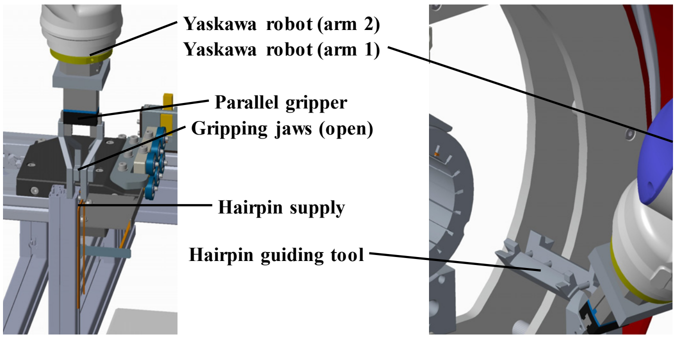

Fig. 14. Cell for the assembly of hairpins

It consists of a parallel gripper and the mounted gripper jaws which pick up the hairpin to be mounted from its supply position. The process, explained also in Fig. 15., starts with the gripping of the hairpin (2). It is transported to the assembly position (3a) and inserted into the stator (3b, 3c). After the pull-in process the transport gripper picks the next hairpin, while the hairpin guiding tool moves to the next slot position. These processes are carried out until the stator is completely filled.

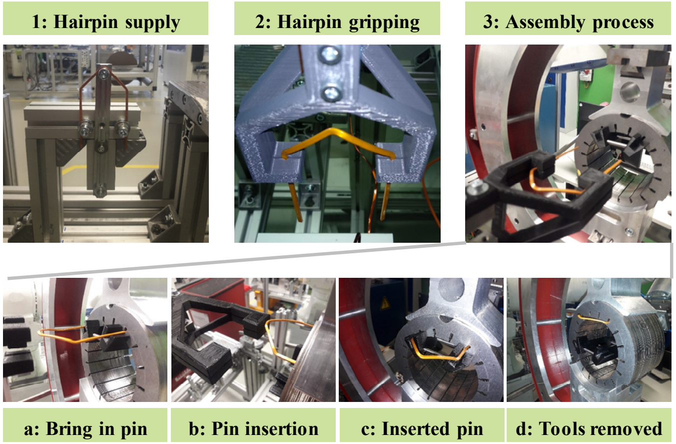

Fig. 15. Robot-based hairpin assembly process

C. Demonstration results

Within the assembly experiments, the ability of robot-based assembly of hairpins could be demonstrated in principle. Especially with the help of the second concept, the individual hairpins could be assembled one after the other without jigs and tools colliding.

VI. SUMMARY AND OUTLOOK

In the automotive industry, electric motors with hairpin coils are increasingly being used to electrify the drive train. On the one hand, this technology saves material. This means that the expensive use of copper can be minimized. On the other hand, the electrical properties can be better than those of conventionally wound electric motors. The aim of the research work presented in this paper was the conception of a robot-based, flexible production of hairpin coils. The focus was on the development of a tool that can be operated by an existing dual jointed-arm robot and its integration into an existing assembly system. It was possible to develop concepts for robot-based forming and assembly of a hairpin coil.

For an economical solution, the equipment must be as cost-effective as possible and highly flexible. In order to demonstrate the basic feasibility of a hairpin production using an industrial robot, the design of a tool that is as flexible as possible was dispensed with. Instead, the focus was on the technical feasibility of such a manufacturing process. For this purpose, a concept was developed with which a hairpin coil can be manufactured by inserting the enameled copper wire into a groove and then separating it from a cutting tool. After the theoretical elaboration, the constructed components were manufactured, then assembled on the test rig, and tested under real conditions.

During the process validation the initially designed bending process was technically confirmed. The production of a hairpin coil is conditionally feasible. However, the coil legs of the electronic component produced in this way are not parallel. This is due to the elasticity of the semi-finished product used. This effect has to be taken into account for future work. Another finding of the process validation was the poor accessibility of the plant layout for the industrial robot. Future work should focus on the revision of the base plate of the bending tool. In order to be able to manufacture a hairpin with parallel legs, it inevitably has to be more over-bent when bending with the robot.

In order to implement the entire process, the system layout must also be considered. By simply turning the tool carrier by 90°, the industrial robot could intervene both in the hairpin production process and in the subsequent stator assembly.

The transportation of the hairpin and the assembly could also be demonstrated. Due to the design of hairpin stators, it is very difficult to assemble the coils successively when the stator fills up due to poor accessibility and friction effects. For future work a robot-based pre-assembly of a hairpin basket is planned, which will then be completely inserted into the stator.

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