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Additively manufactured vacuum grippers for the flexible handling and assembly of hairpin coils in electric motor production

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Abstract

Hairpin technology has recently become the predominant winding technology for the manufacturing of stators used in electric traction motors. In contrast to conventional winding techniques, the manufacturing process chain is based on rectangular wire which is bent into a three-dimensional U-shape – so-called hairpin coils. These hairpin coils have to be individually gripped and assembled to form the stator winding. There can be hundreds of hairpin coils in a single stator, which can also differ in shape. Therefore, gripping and moving the individual hairpin coils is a challenging task in terms of flexibility and cycle time. This paper presents an approach to meet the outlined requirements using additively manufactured vacuum grippers. A concept is investigated in which the vacuum is generated in a conventional vacuum ejector and fed to the vacuum gripper via hose lines. In contrast, the concept of a functionally integrated vacuum gripper manufactured by a new laser-sintering process with automated continuous fibre reinforcement is presented. Based on the laser-sintering process, a lightweight vacuum gripper with an integrated vacuum ejector can be manufactured in a single process step without additional costs for purchased parts. After a review of the state of the art in both hairpin-specific and additively manufactured lightweight grippers, experimental test series are carried out concerning the vacuum quality and the grip strength of the different vacuum gripper designs. Pull-off tests show that high holding forces of several Newtons are possible proving the basic usability of vacuum grippers for hairpins, even though the achievable vacuum quality of the functionally integrated vacuum gripper is lower than that of the conventional ejector. Comparison of the novel approaches with a conventional mechanical hairpin gripper regarding weight, production costs and production time show promising improvements.

Keywords: additive manufacturing; laser-sintering; lightweight construction; continuous fibre reinforcement; hairpin technology; hairpin gripper; vacuum gripper.

1. Introduction

Hairpin technology has been predominant in stators of electric traction motors for several years. The manufacturing process chain is characterized by the use of rectangular wires in contrast to the established round wires. The rectangular cross-section allows for high slot fill factors, resulting in good heat dissipation and, therefore, higher possible current [1]. Hairpin technology is also advantageous in terms of production organization due to its modularity and deterministic processes.

The basic process steps for the manufacturing of hairpin stators have been widely analyzed, e.g. in [2] or [3], and can be described by the bending of the rectangular wire into a multitude of U-shaped hairpin coils (hereinafter referred to as hairpins for simplification), the gripping and pre-assembling of all the individual hairpins in an assembly device to form the desired winding scheme, the insertion of all hairpins into the stator lamination stack, the twisting of the open coil ends and finally the contacting of the coil ends by laser welding. Depending on the stator design, a winding can consist of

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several hundred individual hairpins which in turn can have a variety of different geometries. This makes the pre-assembling process demanding in terms of cycle time and flexibility, as each hairpin must be gripped and placed in an assembly device individually. The corresponding hairpin gripper must be able to securely fixate the hairpins even at high speeds. Furthermore, the necessary flexibility for changes over to different hairpin geometries must be ensured. Known concepts often solve this task with adjustable mechanical grippers resulting in complex and therefore heavy kinematics, high costs and time-consuming set-ups of the gripper.

Therefore, this paper investigates an approach to reduce the mechanical complexity and weight as well as manufacturing time and cost by using additively manufactured vacuum grippers for hairpins. Two different approaches are being investigated here: The use of a purchased, commercial vacuum ejector in combination with an additively manufactured gripper and the functional integration of the ejector into the gripper itself through additive manufacturing. Both variants are compared regarding the vacuum quality that can be generated. The basic usability of vacuum grippers for hairpins is investigated by means of pull-off tests. In addition, both variants are compared to a conventional, adjustable mechanical hairpin gripper in terms of weight, manufacturing time and costs. To manufacture the vacuum grippers, a newly developed laser sintering process with continuous fibre integration is used. Finally, the potential of function integration in additive manufacturing will be illustrated using a complete hairpin gripper from the laser sintering process

2. State of research and technology

2.1. Hairpin geometries

The typical geometry of a hairpin is shown in Fig. 1 on the left. In the middle of Fig. 1, the geometric parameters that are relevant for the gripper are shown. Since the hairpins are usually pre-assembled from the inside to the outside, they are radially gripped from the outside. Therefore, especially the radii r_1 and r_2 of both legs as well as the angle α between the normals of the legs determine the design of the gripper. Depending on the position of the hairpin in the winding scheme, its geometry can differ concerning these geometric parameters. The values for r_1 and r_2 are in the range of about 60-110 mm, those for alpha in the range of about 30-60°.

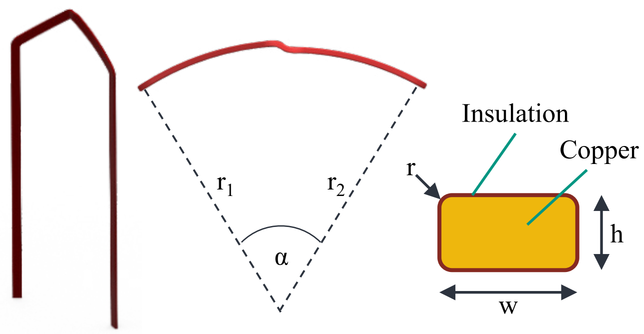

Fig. 1. (left) Typical geometry of a hairpin; (centre) relevant geometric parameters for the gripper (top view); (right) cross-section of rectangular winding wire.

However, it should be noted that these ranges apply to different stators. Within a stator to be produced, the variations between individual hairpins are much smaller. The right side of Fig. 1 shows the cross-section of rectangular winding wire with its width w, height h and edge radius r. The length of the hairpin legs varies with the axial length of different stators, but is not considered in detail here as the influence on the gripper is small. Hairpins of different lengths are gripped at different points on their legs, but the basic geometry of the gripper does not change.

2.2. Hairpin grippers

Although no scientific publications on hairpin grippers in particular are known, it is evident that parallel grippers are generally used for handling rectangular wire in experimental set-ups, e.g. in [4] or [5]. As patents show, parallel grippers are also often used as end effectors in industrial concepts. In many of these concepts, the two end effectors are attached to complex kinematics in order to be able to position them as flexibly as possible according to the specific hairpin geometry; examples for such grippers can be found in [6] and [7]. A schematic structure of a hairpin gripper can be taken from Fig. 2 (left). Two arms (A) are attached to a base unit (B). The arms can be moved rotationally or translationally, which is symbolized by the dotted boxes. The arms in turn hold two end effectors (EE), which ultimately grip the two hairpin legs. The end effectors can also be designed to be movable. The right side of Fig. 2 shows an example gripping pose of an adjustable hairpin gripper. It is obvious that such a gripper is heavy due to its design with several moving elements and actuators, although the hairpin weighs only about 30-60 g. It also involves a lot of development effort and costs. However, the advantage of such a gripper is the minimization of set-up times for new hairpin geometries, as it can be automatically adjusted in a short time.

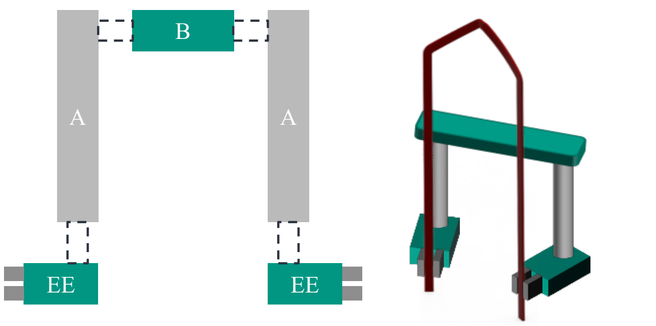

Fig. 2. (left) Schematic structure of a hairpin gripper (B: Base unit; A: Arm; EE: End effector; dotted lines show joints); (right) example gripping pose of a hairpin gripper.

2.3. Additive manufacturing of functionally integrated polymer parts with the laser-sintering process

Additive manufacturing processes offer a promising approach for the kinematic and time-efficient production of Continuous Carbon-Fibre-Reinforced Polymer (CCFRP) parts with a high degree of individualisation and geometric complexity. Material extrusion (MEX) and vat photopolymerisation (VPP) are well established in the literature for the additive manufacturing of functionally integrated parts, such as grippers or clamping devices for use in production [8, 9]. However, parts manufactured by MEX and VPP processes do not optimally meet the quality requirements of the industry. Due to the nature of these processes, support structures are required, which have to be removed and disposed of after manufacturing [10]. This results in the time- and cost-intensive disposal and post-processing steps. In addition, the use of support structures limits the ability to create overhangs, cavities and undercuts – which results in limited part complexity [11]. Furthermore, the removal of support structures can cause surface defects on the remaining part surfaces leading to a more inhomogeneous appearance of the parts. Moreover, MEX and VPP do not allow for economic small-batch production [12]. In contrast, the laser-sintering (LS) process represents a promising alternative for the manufacturing of functionally integrated polymer parts, such as vacuum gripper with internal air channels [13] or with integrated spring without subsequent assembly effort [14]. In a process comparison among MEX, VPP and LS with regard to the mechanical and thermal properties, and the long-term stability of the polymer parts produced, the LS process proves to be particularly advantageous as the LS process enables the production of robust functional parts [15, 16]. Further advantages of the LS process are the absence of support structures and the associated freedom in design. In the LS process, the unsintered powder acts as a support structure, eliminating the need for time-consuming and costly post-processing steps [17]. By realising undercuts, cavities and overhangs, near net-shape functional parts with high complexity can be manufactured by LS in a single process step. Due to the ability for compact vertical and horizontal positioning of parts in the powder bed, the LS process is suitable for the economical production of small batches [15]. In [17], the automated integration of continuous fibres in the LS process increased the mechanical properties of polyamide 12 (PA12) parts in terms of Young's modulus by a factor of 30 and tensile strength by a factor of 8.5 compared to pure PA12 parts. The LS process thus enables the production of robust, highly complex functional parts for series use.

3. Approach and experimental setup

3.1. Approach

First, the two different systems that will be tested in the following are described. The vacuum grippers consist of a vacuum generator unit – called ejector – and an additively manufactured base body containing the air channels and suction cups. The ejector consists of a Venturi nozzle that creates a vacuum at an outlet when compressed air flows through it. The vacuum generation can be located upstream of the base body of the gripper in the form of an external commercial ejector that is connected to the base body with a hose. However, the ejector respectively the Venturi nozzle can also be integrated into the base body by means of additive manufacturing, which reduces the use of purchased parts. In this case, the base body is connected directly to compressed air with a hose. These two types of grippers will be referred to as gripper without function integration (FI) and gripper with FI. The base body of the gripper without FI could also be machined from aluminum, for example, but was additively manufactured here for better comparability.

In order to carry out reproducible tests, two simplified base body geometries printed by LS were initially designed, each containing four oval flat suction cups with a width of 4 mm and a length of 12 mm from J. Schmalz GmbH. Fig. 3 shows the base bodies of the gripper without FI (a) and with FI (c). The corresponding section views (b) and (d) vizualize the air channels and – in the case of the gripper with FI – the Venturi nozzle (d). For further functional integration, the gripper with FI is equipped with printed connections for the flat suction cups. In the case of the gripper without FI, threaded inserts are used to create a secure connection point between the additively manufactured base body and the flat suction cups. The gripper connections for vacuum (without FI) or compressed air (with FI) on the top of the base bodies are designed as M5 threads and can be used accordingly, for example, with 4 mm diameter hoses.

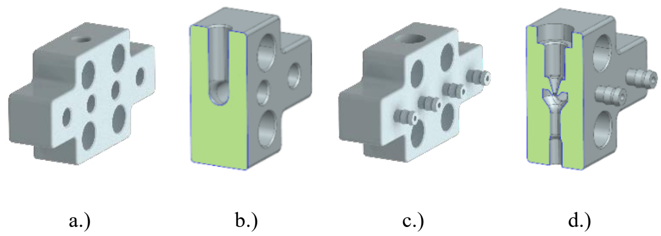

Fig. 3. Base bodies of the gripper without function integration (a) and with integrated Venturi nozzle (c). Section view through the correponding grippers (b and d).

3.2. Measurement of vacuum quality

First of all, the achievable vacuum quality of both commercial and additively manufactured ejectors is investigated. For this purpose, the ejectors listed in Table 1 are examined. Commercial ejectors are available with various characteristics that generate a high vacuum or a high suction volume flow; however, only those with a high vacuum have been tested.

Table 1. Tested ejectors for vacuum quality.

Ejector	Variant
Commercial ejectors	small
(Festo Vertrieb GmbH & Co. KG)	middle
	large
Additively manufactured	-

A vacuum meter is used to measure the vacuum. In contrast to commercial ejectors, the vacuum measurement in the gripper with FI cannot be directly taken at the outlet with a simple connection. Hence, hoses are connected to the four outlets provided for the suction cups and interconnected so that the vacuum meter can be connected. In addition, three hoses can be sealed and the vacuum measured on the fourth hose. In this way, it can be ensured that all channels in the base body are open and have not been closed during the additive manufacturing processes.

For later estimation of operating costs, the volume flow of the supplied compressed air is also measured. The air pressure is increased in 1 bar steps from 1 bar to 7 bar. For the commercial ejectors, the pressures specified by the manufacturer for maximum vacuum were also set. The schematic set-up for determining the vacuum quality can be seen in Fig. 4.

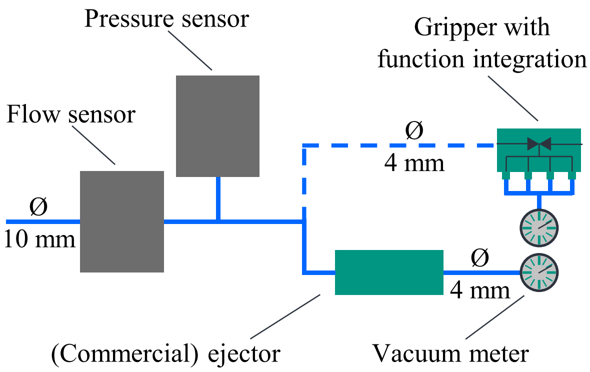

Fig. 4. Schematic set-up for determining the vacuum quality for commercial ejectors and function-integrated gripper (dotted line).

3.3. Measurement of holding force

The next step is to determine the achievable holding force of the vacuum grippers on a real material with pull-off tests. For this purpose, a straightened piece of rectangular wire with a width of 6.3 mm and a PEEK insulation is clamped on a load cell from burster präzisionsmesstechnik gmbH & co kg (type 8524-5500). The grippers are mounted with a quick change system on a Kuka KR 10 robot. The industrial robot positions the gripper over the wire so that all suction cups are in reliable contact. Then, the robot moves at minimum speed in the upper z-direction until the holding force of the gripper is exceeded and the suction cups detach from the rectangular wire. The experimental set-up is shown in Fig. 5.

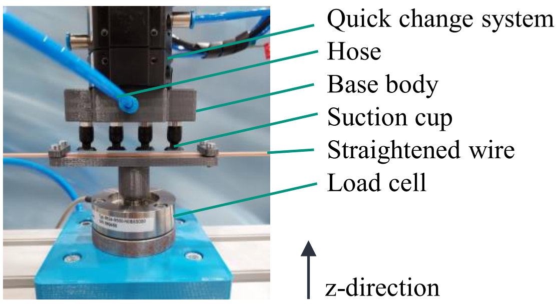

Fig. 5. Experimental set-up for measuring the holding force.

The theoretical holding force of a suction cup $F_{theo,SC}$ can be calculated by multiplying the difference Δp between ambient pressure and system pressure by the effective suction area A of a flat suction cup [18]. The theoretical holding force of the gripper F_{theo} can be determined by multiplying $F_{theo,SC}$ by the number of suction cups n, see equation (1).

$$F_{theo} = \Delta p \cdot A \cdot n \quad (1)$$

The gripper without FI is combined with two different commercial ejectors. For each variant, the air pressure for maximum vacuum mesured during the vacuum quality tests was set. The entire experimental plan can be found in Table 2.

Table 2. Experimental plan for the measurement of holding force.

Gripper	Variant	Air pressure [bar]
Without FI	Ejector small	4.7
Without FI	Ejector large	3.7
With FI	-	6

As shown in Fig. 6, flat suction cups can compensate a certain angular misalignment β due to their elastic design. To investigate the effect of such angular misalignment on the holding force, further pull-off tests are performed in which the gripper is tilted by angles of 5°, 10° and 15° by the robot.

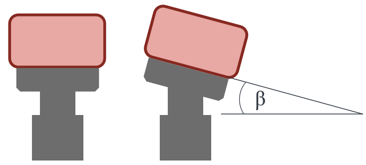

Fig. 6. Compensation of angular misalignment β by flat suction cups.

4. Results and discussion

4.1. Vacuum quality

The test results on the determination of vacuum quality can be taken from Table 3. A value of 80 % means a pressure difference Δp of 0.8 bar respectively an absolute value of 0.2 bar. The displayed air pressure and volume flow were measured at the highest vacuum. The measured values of the commercial ejectors differ only very slightly from the specifications regarding vacuum quality and the corresponding air pressure. It can seen that the vacuum quality of the additively manufactured ejector is only about half as good as the commercial one with higher air consumption at the same time.

Table 3. Measured vacuum quality for different ejectors.

Ejector	Variant	Highest vacuum [%]	Air pressure [bar]	Volume flow [l/min]
Commercial ejectors	small	88	4.7	24
	middle	89	4.5	42
	large	91	3.7	330
Additively manufactured	-	44	6	59

4.2. Holding force

With a cross-sectional area of the suction cup of 30 mm², 4 suction cups and the vacuum pressures determined in Table 3, the theoretical holding forces for the grippers are as listed in Table 4. The corresponding real forces were measured in three tests per gripper and averaged. As can be seen, theoretical and measured forces differ by 6-13 %, which can have different reasons such as leakage in the system. The higher measured force for the gripper with FI could be due to the fact that the vacuum measurement described in Fig. 4 is subject to greater leakage than when suction cups are connected. In order to keep the number of experiments low, no tests were carried out with the middle-sized ejector.

Table 4. Holding forces for different set-ups.

Gripper	Variant	Theoretical force F_{theo} [N]	Measured force F_m [N]	F_m / F_{theo}
Without FI	Ejector small	10.56	9.97	0.94
Without FI	Ejector large	10.92	9.45	0.87
With FI	-	5.28	5.68	1.08

The measurement of holding forces with angular misalignment β was carried out for the gripper without FI in combination with the large ejector as well as the gripper with FI. The results can be seen in Fig. 7. Up to an angle of 10°, only a slight reduction in the holding force of 5 % for the gripper with FI and an increased reduction of 30 % for the gripper with FI is observed. For an angle of 15° a reduction in the holding force of more than 50 % can be observed for both variants.

These results show that the holding force in the z-direction is sufficient to securely fixate a rectangular wire of 30-60 g even at high accelerations. In addition, angular deviations between the wire and the gripper, such as may occur due to the bending process of the hairpins or the production process of the gripper, can be compensated for up to an angle of 10 degrees without any major loss of force. However, future experiments will have to be conducted to determine the extent to which the simplified tests performed can be transferred to a real hairpin geometry. In addition, tests must be carried out to determine the pull-off force in the axial direction of the hairpin, which is relevant for the assembly of the hairpins into the assembly device.

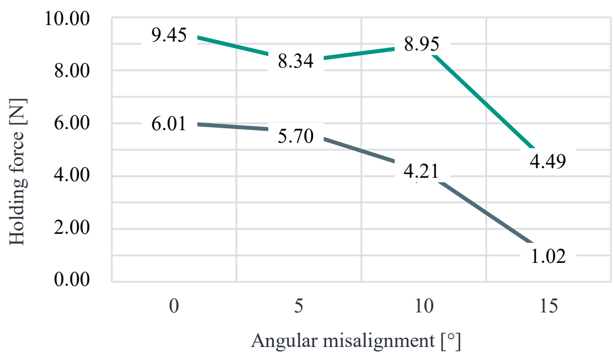

Fig. 7. Holding forces for the gripper without FI in combination with the large commercial ejector (green) and the gripper with FI (grey) depending on the angular misalignment β.

4.3. Estimation of costs

Fig. 8 shows an LS-printed vacuum hairpin gripper. It is attached to a robot with a quick change system and contains four suction cups for each hairpin leg. The gripper can be produced with or without FI. A list of the approximate costs

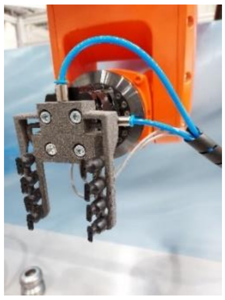

Fig. 8. Vacuum gripper for hairpins printed with the LS-process.

can be found in Table 5 for a hairpin gripper as it is shown in Fig. 8 with and without FI and an adjustable mechanical gripper as described in 2.2. However, costs may vary depending on the provider, purchase quantity and variant, and should therefore be considered an estimate only. It is especially difficult to estimate the cost of adjustable mechanical hairpin grippers because they are not standard parts. A conservative calculation with 2 small pneumatic parallel grippers (€200 and 50 g each), 2 servo motors (€1,500 and 700 g each) and an aluminum frame (€500 and 700 g) results in the stated material costs of €3,900 and a weight of 2,200 g. Additional accessories such as screws or pneumatic connections were not considered here. For the additively manufactured grippers, powder costs (€95) and eight suction cups (€10 each) are calculated. Costs of €80 are assumed for the commercial ejector. With a measured mass of 40 g, the gripper is many times lighter than a mechanical gripper. Manufacturing time is 450 minutes for the additively manufactured grippers (heating: 80 min, printing: 70 min, cooling: 240 min, assembly: 60 min) and estimated 1000 minutes for the mechanical gripper (milling: 600 min, assembly: 400 min). Assuming €40 per machine and working hour, this results in the listet production costs. Table 5 shows that additively manufactured vacuum grippers are significantly cheaper than adjustable mechanical grippers. However, it must be noted that these grippers can only grip a single hairpin geometry. Therefore, several grippers corresponding to the number of different hairpins in the stator are required. To realise short cycle times, a quick-change system might be necessary, which further increases the costs of every gripper. The costs of an ejector, on the other hand, is a one-off expense as it can be located upstream of the quick-change system. In addition, the increase of manufacturing costs (except assembly time) for LS-printing multiple grippers is negligible because all grippers can be produced simultaneously on the same powder bed, which is a great advantage of the LS-technology. For a stator with seven different hairpin geometries, this results in costs of approximately €1,800 and €2,400 for LS-printed grippers with and without FI compared to €4,570 for a mechanical gripper. Costs for a quick-change system are not included here.

Table 5. Approximate expenses for producing additively manufactured vacuum hairpin grippers with and without FI and adjustable mechanical grippers.

Expenses of gripper	with FI	without FI	mechanical
Material costs [€]	175	255	3,900
Manufacturing costs [€]	300	300	670

In addition, the operating costs for a vacuum gripper are to be roughly calculated following [19] and the results of the vacuum quality tests. For this purpose, a cycle time of 4 seconds for gripping and pre-assembling a single hairpin is assumed. With 250 working days and a three-shift operation, this results in a hairpin number of 5,400,000 per year. If a conservative estimatation is made, it can be assumed that the ejector is used for 3 seconds per hairpin (since it does not need to be switched on if it is not gripping a pin), resulting in operating time of 270,000 minutes per year. Assumed costs of €0.025 per m³ of compressed air result in the operating costs listed in Table 6. These costs could be further reduced by using ejectors with energy-saving functions. Nevertheless, they also show the great relevance of a correct layout of the system respectively the avoidence of oversizing the ejector.

Table 6. Operating costs estimation for different set-ups.

Gripper	Variant	Volume flow [m³/min]	Costs per year [€]
Without FI	Ejector small	0.024	162
Without FI	Ejector large	0.330	2,228
With FI	-	0.059	398

5. Conclusion and Outlook

This paper has shown the possible use of additively manufactured vacuum grippers for hairpins by an experimental proof of concept. Pull-off tests showed that high holding forces of several Newtons are possible, even with angular deviations of up to 10 degrees, proving the basic usability of vacuum grippers for hairpins. The tests were carried out with a vacuum gripper without function integration in combination with an upstream commercial ejector and with a function-integrated gripper with an LS-printed Venturi nozzle. The holding forces of the function-integrated gripper were about half those of the gripper with a commercial ejector. By using the LS-process, the weight as well as the costs and manufacturing time of a gripper can be significantly reduced compared to adjustable mechanical hairpin grippers. The use of parameterized CAD models enables rapid generation and manufacturing of new grippers. The vacuum gripper is also easy to control, as it only requires a single pneumatic valve and not inverters for servomotors. In addition, hardly any purchased parts are required, especially for the gripper with function integration. However, it should be noted that the number of grippers required for the assembly of a stator depends on its number of different hairpin geometries, whereas an adjustable mechanical gripper can be used for a large number of different hairpins. Because of the quick-change system required, cycle times are expected to be longer than with the mechanical gripper, which makes its use particularly likely in prototype production and small series. Future tests must show that the results of the tests carried out with simplified grippers on single wires can also be achieved for real hairpins and more complex grippers.

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