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Additive Manufactured, Topology-Optimized Grippers for Collaborative Robotics in Hairpin Stator Prototyping and Assembly

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Abstract

The automotive industry is undergoing profound change, driven by the global climate crisis and the scarcity of resources. To achieve international climate targets, the electrification of the powertrain is becoming increasingly important. The resulting increase in demand for electrically powered vehicles requires a diversification of electric engine Hairpin stators with rectangular copper conductors, which offer advantages over conventional windings thanks to the higher fill factors. Nonetheless, the increasing diversification of the design imposes considerable demands on production systems. It is a common occurrence that processes and systems remain in prototype status during the preliminary phases of the production ramp-up. This study presents a novel approach for the flexible automation of hairpin stator assembly in prototyping. The approach combines collaborative robotics with additively manufactured, topology optimized grippers. The focus of the investigation is on the structural optimization of a variant-adaptive robot gripper based on polylactide. The optimization of the grippers in terms of mass, volume and structural stiffness was carried out using an iterative topology optimization in combination with the static finite element method. The results demonstrate that through targeted optimization, a mass reduction of more than 25 % could be achieved while maintaining the same mechanical stiffness compared to the reference model. At the same time, the structural efficiency was significantly increased. The manufactured gripper fulfills all functional requirements in application tests with different hairpin geometries. The resulting weight reduction contributes to the energy efficiency of the overall system and supports sustainability goals by minimizing the use of materials. The study confirms the potential of additive manufacturing in combination with topology optimization as a key technology for sustainable, flexible automation in multi-variant production environments. The methodology developed can be transferred to other applications in the field of robotics and additive manufacturing and contributes to the resource-saving series production of individualized functional elements.

Keywords: Additive manufacturing, Topology optimization

1. Introduction

The transition towards electrified mobility represents a paradigm shift in industrial value chains, extending far beyond a mere technological trend. This shift is driven by regulatory measures to mitigate greenhouse gas emissions, the increasing scarcity of finite resources, and societal demands for sustainable production [1-3]. To avert further climate change-related impacts, many countries have set ambitious goals for reducing carbon dioxide (CO_2) emissions. Germany, for example, aims for climate neutrality by 2045 and has implemented measures across all sectors [4, 5]. Road transport remains a key focus, as it accounts for a significant share of CO_2 emissions. Electrifying the automotive sector offers substantial reduction potential, since battery electric vehicles (BEV) emit no direct greenhouse gases during operation. Within this framework, the production and design of electric motors plays a central role in meeting climate targets. Among recent innovations, hairpin technology has gained prominence. This technology replaces conventional round stator wires with rectangular copper conductors, enabling a higher copper fill factor k_{Cu} and thus increasing motor power density P and efficiency η [6, 7]. However, hairpin stator production is complex, requiring specialized tools and machinery tailored to specific stator variants, leading to high investment costs. Manufacturers must therefore adapt production systems to remain competitive. A crucial process step in hairpin stator production is the controlled separation of hairpin ends before twisting and welding. This process step demands precise handling to maintain conductor alignment and prevent mechanical damage. While automated systems designed for mass production are in principle capable of meeting these requirements, they often fail to provide the necessary flexibility to cope with the growing variety of new stator designs. The use of collaborative robots (cobots) offers a promising alternative to automated systems designed for mass production, as they combine flexibility, safe human-robot interaction, and rapid adaptation to different product variants [9, 10]. The overall performance of cobot-based automation systems is largely determined by the design of their gripping tools, as these directly influence precision, reliability and adaptability to varying hairpin stator geometries. Here, additive manufacturing (AM) combined with topology optimization (TO) enables the rapid development of lightweight, structurally optimized grippers tailored to a specific task [11-13]. Beyond functionality, AM and TO can contribute to sustainability by reducing material consumption through weight minimization. Lower gripper mass m_{gr} decreases resource use and reduces the cobot's operational energy demand and enhances the cobot's dynamic performance, thereby supporting broader energy-efficiency and emissions-reduction goals.

2. State of the art

2.1. Hairpin-stator manufacturing and flexible automation

In recent years, hairpin technology has emerged as a pivotal design concept for electric motors. The use of rectangular copper conductors enables a much denser slot filling, achieving copper fill factors of $k_{recCo} \geq 0.70$. In comparison, conventional round-wire windings, reach only copper fill factors of $0.45 \leq k_{rwCo} \leq 0.5$ [6-7]. As previously delineated, this increased copper fill factor k_{recCo} enhances electrical efficiency η, boosts power density P, and facilitates more compact motor designs. Production of hairpin stators is a complex process involving sequential, tightly controlled steps [8]:

- mechanical wire processing such as straightening, insulating, bending,
- assembly into the stator and
- joining processes such as cutting, twisting and welding.

A particularly critical step is the separation of hairpin ends prior to twisting. The wire ends must be positioned in a precise pattern to ensure proper joining. Automation of this step is challenging, especially in low-volume production or when dealing with high variability in stator geometry. Conventional industrial automation, optimized for high throughput and standardized product geometries, frequently lacks the flexibility to accommodate such variation [9]. Furthermore, tool sets and fixtures tailored to specific stator variants can incur substantial costs. In light of the increasingly diverse range of e-mobility variants, there is an urgent need for automation solutions that are both flexible and economically viable for small and medium batch sizes.

2.2. Topology optimization of additive manufactured grippers for agile hairpin stator production

As previously outlined, the increasing complexity and variability of hairpin stator production necessitate automation solutions that combine precision, adaptability, and cost-efficiency, even in small to medium batch sizes. Conventional automation systems, while effective in large-scale, standardized production, often reach their limits when frequent design changes, customized process steps, and flexible handling are required. Cobot based systems address these challenges by combining precision with adaptability, making them a promising solution for such demanding manufacturing environments. In these systems, the performance of the cobot is determined not only by its kinematic, dynamic, and control capabilities but also by the design of its peripherals. The end effector is of particular significance in this regard, as it forms the direct interface to the workpiece and directly influences process quality.

In recent years, AM has evolved from a rapid prototyping tool to a well-established process for producing functional, load-bearing components. Within the field of handling technology, this development enables the rapid fabrication of customized grippers with intricate geometries, such as internal channels, conformal surfaces, and variable stiffness k regions, features that are difficult or impossible to realize through conventional manufacturing methods. When combined with TO, AM offers an even greater potential. TO applies computational algorithms to remove non-load-bearing material, resulting in lightweight, structurally efficient designs that maintain the required structural stiffness k while minimizing mass m. Cobots have been identified as particularly well-suited for pairing with AM and TO-designed grippers. Their ability to operate safely without protective enclosures, combined with rapid reprogramming, supports agile production strategies in the e-mobility sector [10-12]. Furthermore, it has been demonstrated that the utilization of lightweight TO grippers reduces the effective payload, thereby decreasing operational energy consumption and improving dynamic behavior. The integration of AM and TO into end-effector development shortens development cycles, reduces manufacturing costs, and enables a high degree of application-specific customization. These combined advantages directly address the challenges of hairpin stator production. As a result, AM and TO can be regarded as key enabling technologies for the next generation of flexible, high-performance handling systems in electric motor manufacturing [13-14].

3. Methodology for optimization of a gripper for hairpin separation

The present study proposes an integrated methodology for the development and evaluation of a gripper for a cobot, designed for the separation of hairpins in stator assemblies. Numerical simulation, experimental validation, and AM are systematically combined within a four-stage workflow. In the first stage, a finite element analysis (FEA) of the complete hairpin separation process is developed using process simulation. This FEA provides detailed insights into the expected load conditions and establishes the basis for subsequent TO. In the second stage, experimental bending tests are conducted on individual hairpins to characterize their mechanical response and material properties. Particular attention is given on the analysis of their force-displacement behavior. The numerical results are then compared with the experimental data for validation. The third stage involves the design and AM of a topology optimized gripper, aiming to generate a lightweight geometry that meets the functional requirements of the separation process. Finally, in the fourth stage, the manufactured gripper is integrated into a cobot system, and evaluation experiments are carried out under realistic operating conditions.

3.1. Simulation-based analysis of hairpin separation using a gripper-stator model

The FEA were carried out using the Ansys® Structural Analysis Toolbox from Ansys Inc., Canonsburg, United States, in order to obtain profound insights into stress displacement distribution during the complete hairpin separation process. The simulation replicates the sequence of movements of the real manufacturing process, quantifies the forces F and deformations Δl occurring during separation, and identifies critical load cases for subsequent optimization. To ensure an appropriate balance between computational effort and model fidelity, reasonable simplifications regarding geometry were made. Concerning symmetry of the model, a representative section consisting of six radially aligned hairpins, insulation paper, and a partial segment of the laminated core was modelled. A coarse geometric model of the existing gripper was integrated into the FEA together with the simplified hairpin stator as a computer aided design (CAD) model. A prescribed displacement was applied to the gripper, according to the requirements of the subsequent twisting process. This boundary condition corresponds to the actual mechanical interaction in the separation process. For the structural representation of both the gripper and the hairpins, appropriate material models were defined: The polylactide (PLA), used for the gripper, was modelled with a purely elastic model, and copper, used for the hairpins, was modelled with a nonlinear elastoplastic material model including isotropic hardening. The relevant material parameters are summarized in Table 1. Figure 1, shows the global deformation Δl at the end of the separation process as a main result of the simulation.

Table 1 Material parameters
for hairpins made of copper and gripper made of PLA

Material	Copper	PLA
Elastic modulus E_0	110 GPa	2.85 GPa
Poisson's ratio ν	0.34	0.35
Density ρ	8.30 g/cm³	1.24 g/cm³
Tangent modulus E_t	1.15 GPa	
Yield strength σ_y	0.28 GPa	

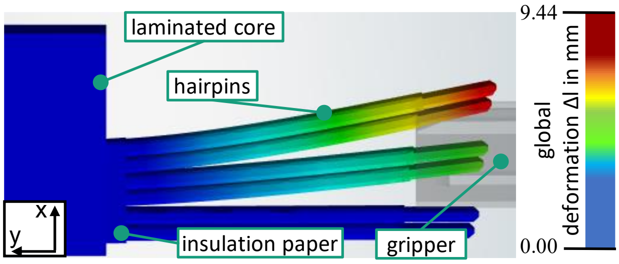

Figure 1. Global deformation Δl of the hairpins as result of the simulation

3.2. Bending test for validation of simulation results and load case determination

To validate the simulation results and to define reliable load cases for the subsequent TO, the hairpin separation process was experimentally reproduced by means of a bending test. For this purpose, a universal testing machine of type T1-FR150SN.A4K from ZwickRoell GmbH & Co. KG, Ulm, Germany, was employed. The hairpin specimens were clamped at one end and positioned in a specially designed bending device that permitted only horizontal relative motion of the hairpin specimens. Load was applied by vertically displacing the device at a constant velocity v up to a maximum deflection of l_{max} = 30 mm. During the tests, the forces F acting in the course of the separation process were recorded. These data primarily served for comparison with the numerical simulations and thereby for the validation of the FEA. Deviations between simulation and experiment were observed mainly in the transition from the elastic to the plastic region. This discrepancy can be attributed to the simplified material model used in the FEA, in which a nonlinear elastoplastic material model including isotropic hardening was applied.

3.3. Topology optimization and additive manufacturing of the gripper

The main objective of the TO process was to achieve a substantial reduction in gripper mass m_{gr} while simultaneously maintaining the required structural stiffness k. This requirement is of particular importance in cobots, where the limited payload capacity directly affects system performance and flexibility. The TO was carried out using the Ansys® Topology Optimization Toolbox from Ansys Inc., Canonsburg, United States. As a starting point, the coarse geometry of the manufactured gripper was imported into the simulation environment as a CAD model. Within the optimization setup, particular emphasis was placed on preserving functionally critical areas, such as the contact zones between the gripper jaws and the hairpins. These were defined as non-design regions to prevent material removal and to guarantee reliable force transmission during the separation process. The remaining design space was subject to optimization, with the material volume V restricted to 70 % of the initial model in order to balance weight reduction and structural integrity. The maximum payload capacity of the cobot type UR16e from Universal Robots A/S, Odenese, Denmark, specified as F_{Cobot} = 160 N, was defined as the critical load case and implemented as a central boundary condition. Figure 2 shows the AM gripper after completion of the TO.

Figure 2. AM gripper after completion of the TO

Subsequent to the manufacturing process, the gripper was integrated into the existing cobot-assisted separation station, as illustrated in Figure 3. For experimental validation, a UR16e cobot from Universal Robots A/S, Odense, Denmark was employed. The hairpin stator, fully equipped and insulated, was mounted on a rigid baseplate to ensure reproducible boundary conditions and to emulate the industrial assembly processes. In Table 2, the relevant characteristics of the gripper are shown both in the initial state and after the TO.

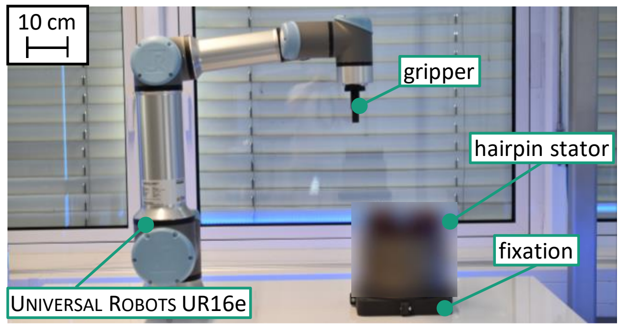

Figure 3. Experimental setup;
fully equipped hairpin stator and a cobot of type UR16e
from Universal Robots A/S equipped with the TO and AM gripper

Table 2 Overview of the
physical parameters of the gripper in the initial sate and after TO

Physical parameters	Initial state	TO gripper
Mass m	63 g	43 g
Volume V	50.75 cm³	35.08 cm³

The findings underline the potential of TO and AM methodologies as enabling technologies for future generations of adaptive, cobot-based handling systems in the e-mobility sector.

4. Results and discussion

The gripper was integrated into the existing test setup and mounted on the cobot. The cobot program was subsequently adjusted to ensure precise alignment with the geometry and kinematics of the new gripper. Deliberately, no external sensors were used to record the process force F during the separation process. Instead, the integrated force-torque sensor in the cobot was used to enable continuous recording of process force F and torques M. Therefore, the process force F could be recorded in real time throughout the entire process without the need for additional measuring hardware. To ensure the statistical reliability of the results, complete separation cycles at ten hairpin positions resulting in different cobot poses were carried out, with each cycle repeated five times under identical boundary conditions. The box plots in Figure 4 illustrate the distribution of the maximum process forces F_{max} across the ten examined hairpin positions. At first glance, there is no indication that the measurements obtained in the present experimental setup deviate fundamentally from a normal distribution. Nevertheless, the position of the median values, in some cases markedly shifted towards the interquartile boundaries, indicates that either the sample size is insufficient, the distribution exhibits a significant skewness, or additional, as yet unaccounted factors influence the measurement results. The global mean maximum force amounts to $\overline{F_{max}}$ = 52.29 N with a standard deviation of σ = 4.06 N. In this case, the confidence interval is calculated as: [$\overline{F_{max}}$ - 3 σ, $\overline{F_{max}}$ + 3 σ] = [42.13 N, 66.46 N]. The majority of the measured values fall within the confidence interval, indicating a generally high repeatability of the measurements. Moreover, hairpin positions 1, 8 and 10 proved appear to be favorable with respect to the stability and reproducibility of the separation process. These hairpin positions were characterized by narrow interquartile ranges, reflecting high repeatability. However, hairpin positions 2, 5, 6, and 7 exhibited a broader dispersion. In practice, such variabilities can result from geometric tolerances in hairpin manufacturing, minor alignment deviations, pose-dependent variations in the overall cobot stiffness k, or slight deviations in the gripping point of the tool. A single outlier, observed at hairpin position 9, is most likely caused by a slight tilting of the hairpin or uneven plastic deformation ε_d during separation. As this is an isolated case without systematic accumulation, it does not indicate fundamental process instability.

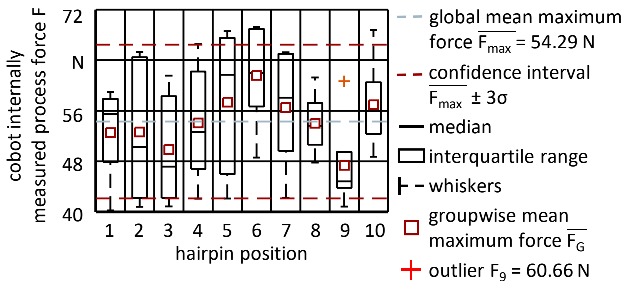

Figure 4. Distribution of maximum process forces F_{max} at ten hairpin positions

5. Conclusion

The present study demonstrates the successful development, simulation and experimental validation of a TO and AM gripper for the automated separation of hairpins in hairpin stator assemblies. By combining numerical process simulation with AM a functional and weight optimized gripper prototype was realized, specifically tailored to the requirements of cobots. Experimental investigations employing the integrated force torque sensor of the used cobot confirmed that the separation process can be performed with high repeatability and within a stable range of process force F. A statistical evaluation of the recorded maximum process forces F_{max} further revealed that variations between individual hairpin positions remain moderate, while the overall process exhibits a high degree of reproducibility. These findings highlight that the presented methodology, consisting of comprehensive process simulation, targeted TO and AM, constitutes an effective approach for designing flexible and efficient cobot assisted handling systems in the field of electric motor manufacturing.

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