Highly Modular Postprocessing by Robot Kinematics in an Additive-Subtractive Manufacturing Process for Polymer Components

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Abstract

Additive manufacturing processes have the potential to economically address the trend towards greater individualization and shorter product availability driven by globalization and digitization. In addition, future products will need to meet regulatory requirements for reparability to prevent increasing resource scarcity. By repairing products, an extension of the product life cycle can be achieved and, in particular, material resources can be saved. In the context of a shortage of skilled workers, future manufacturing processes must be as flexible as possible to meet a wide range of requirements. In the field of electromobility, the high volatility of the market presents special challenges for production engineering. To meet all these challenges, a highly flexible machine for the additive-subtractive manufacturing of highly functional polymer components was developed. With the help of this process chain with inline process control and an industrial robot for the integration of subcomponents, it is intended to make fully automated post-processing, repair and modification of multi-material components using the fused filament fabrication process possible.

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1 Introduction

There is an increasing demand for customized products, for which additive manufacturing processes are particularly suitable due to their high flexibility. The fused filament fabrication (FFF) process is characterized by comparatively simple machine technology, low production costs and short production times. However, the main disadvantages are the rough surfaces, insufficient dimensional accuracy and the need for support structures in case of overhangs. This results in a high level of manual and time-consuming post-processing effort and a loss in part quality. Especially for surface-critical applications, this can exceed the manual effort of conventional manufacturing methods [1]. As a result, the application is limited to prototyping, and the potential in the area of series production of individual components remains unused. At the beginning of the COVID-19 pandemic, for example, many protective masks were additively manufactured [2]. The raw material cost of the FFF process is comparatively low since hardly any waste is produced. Under these conditions, series production of individualized parts using 3D printing is in theory economically feasible. However, the time and cost of manual post-processing is high [3].

Due to critical requirements many complex vehicle components are designed as functional, hybrid polymer parts, which are, however, difficult to access for repairs of the functional interior (e.g. electronics). This, though, contradicts the "right to repair", which is stated in a resolution of the EU Parliament as a requirement for manufacturers "…to design their products in such a way that they last longer, can be repaired reliably, and their parts are easily accessible and removable…" [4, 5]. The aim is a long, resource-saving lifetime with the possibility of reusing and modifying individual components. To achieve this in a resource-efficient manner, it must be possible to reclaim existing parts and adapt their functions. In general, the FFF process is suitable as a primary approach, but it must be extended to include additional process elements [6]. These include the fully automated integration of inserts (load introduction elements, electronics, etc.) into the printing process using a robot [7]. Subtractive pre- and post-processing significantly improve dimensional and surface quality. In combination with a non-planar additive manufacturing strategy, the potential of this process chain for the production of complex structures has been demonstrated [8, 9].

Commercially available products are highlighted that offer a combination of additive manufacturing and post-processing steps are highlighted below. Combined printing and milling systems already exist for large components, such as CEAD's AM Flexbot [10] and Thermwood's LSAM [11]. These products have no sensors, which makes automated quality control and reactions to print errors impossible. The effector (extrusion or

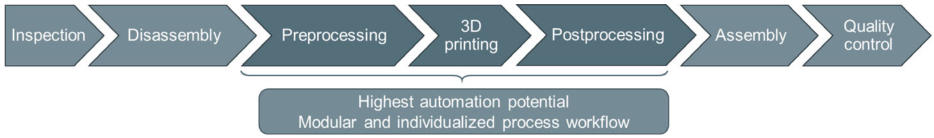

Fig. 1 Exemplary workflow for manufacturing, repair and upgrading of 3D printed parts through an additive-subtractive manufacturing process combined with various pre- and postprocessing

milling) cannot be changed automatically. In addition, both systems only allow an initial printing and subsequent milling of the surface. Integration of other components or connecting parts is not possible. The companies Rösler Oberflächentechnik GmbH [12] and Additive Manufacturing Technologies Limited [13] offer a variety of machines for automated post-processing of additively manufactured parts from powder bed fusion processes. These machines can remove powder residue and support structures from parts as well as smoothen their surfaces. Automated robotic part loading is available in some cases. Support structures can only be removed sequentially and individually. Thus, only partial automation is possible. As a result, due to increasing price pressure, customers continue to prefer the less expensive mass-produced parts.

Automated additive manufacturing processes currently only exist as research projects and for powder bed fusion. A few semi-automated individual modules are available [14]. A comparison with the state of the art clearly shows that a system for the fully automated production of ready-to-use FFF parts does not yet exist. To achieve this functionality, modules from different manufacturers would have to be combined at a high cost and part handling would have to be fully automated.

In the context of extended functional integration and the repairability of additively manufactured polymer components, a process chain as shown in Fig. 1 offers significant advantages. The combination of different manufacturing principles enables the efficient production of highly functionalized, customized, hybrid polymer components. Furthermore, an increase in the number of variants can also be realized after the manufacturing process or during the life cycle, as the process enables modification or targeted repair of used components. Based on the requirements and an existing 3D printer, fully automated post-treatment and additive repair are addressed in two new projects. In this paper, the existing system is presented first, followed by a conceptual implementation of the extended process chain and finally two use cases for post-processing and repair.

2 Basics

In the context of the increasing demand for individualized functional components and the associated need for flexible production machines, this chapter presents a hybrid additive-subtractive fused filament fabrication (FFF) process with a milling spindle and handling robot (2.1). This machine concept aims to maximize the degree of automation and minimize the use of manual activities by workers. In 2.2, the current workflow of digital process planning is presented using the so-called “HybridPlaner”.

2.1 Additive-Subtractive 4 K-FFF-Process

As part of the “InnovationsCampus Future Mobility”, a novel additive-subtractive manufacturing process for the production of function-integrated polymer components was developed. The basis of this additive-subtractive manufacturing process is an FFF module with four nozzles (multi-material printing—4K) and four axes of motion (x, y, z, C). An AMB 1050 FME-P DI 230V milling spindle from AMB-Elektrik GmbH was mounted on the extruder portal to reduce the manufacturing inaccuracy of about 0.3 mm which is typical for the FFF process. This eliminates play or high process forces during the integration of functional components by increasing the manufacturing accuracy to 0.02 mm. The machine also has a KUKA KR6 HA handling robot from KUKA GmbH for integrating the functional components during FFF printing. Figure 2 shows the basic process flow of the 4K FFF system.

In the first step, the basic structure is produced using the FFF process. The cavity, i.e. the negative shape of the part to be integrated, is already provided in the CAD model and is not filled with a support structure during the printing process. In a layer defined by the user, the printing process is paused at the machine’s zero point and thus the measurement of the cavity is started using a 2D camera. An external image processing program is used to compare the target dimension with the actual dimension. The difference or the remaining oversize is transferred to the control of the FFF module and converted into a milling cycle (circular pocket, rectangular pocket, etc.). At the end of the milling cycle, the pocket is checked again. If the pocket is too large, i.e. the dimension of the pocket

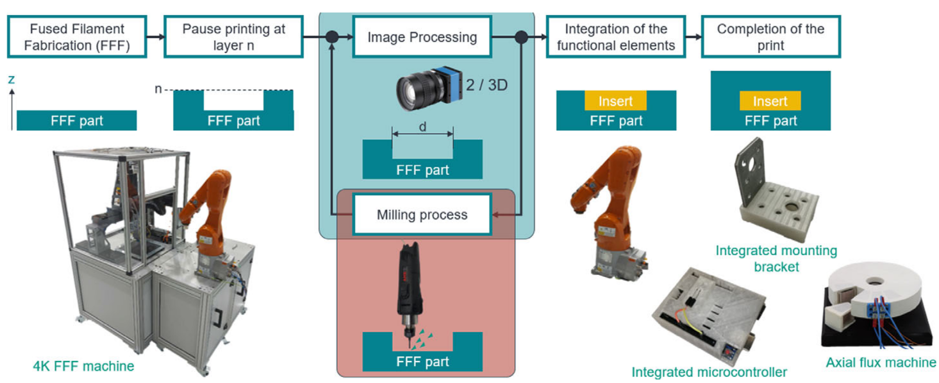

Fig. 2 Process flow of function integration

is out of tolerance, the machine goes into standby mode. The user receives an e-mail notification of the current machine status. If the cavity is within the specified tolerances, the industrial robot is activated. The robot picks up the insert to be placed using a gripper (suction gripper, parallel jaw gripper or similar) on the passive module provided.

The entire CNC code with printing code, milling commands and position data for the robot are generated with the help of the so-called “HybridPlanner”—see Sect. 2.2. After the insert is placed, the printing process is continued and thus the insert is completely embedded in the FFF structure. Fig. 2 (right hand side) shows three components that were produced using the 4K FFF process. These components are FFF parts with embedded steel brackets as force introduction or fixing elements to other components. An Arduino MEGA with an FFF-printed protective case is also shown. Furthermore, by processing conductive filament as well as by integrating temperature sensors and threaded inserts as connection points for the power supply, it was possible to produce complete sensor circuits [9]. Such sensor circuits are used in [8] to measure the winding temperature of an axial flux machine for condition monitoring.

2.2 Process Control and Process Planning

The developed 4K FFF machine is controlled by a Beckhoff programmable logic controller (PLC) with a computer numerical control (CNC) extension. With the help of this CNC extension, it is possible to process CNC codes containing the print and milling data of the FFF component to be produced following DIN 66,025. The target positions of the inserts in the FFF part, which are stored in the CNC code, are transmitted bit by bit to the robot controller (KUKA KRC4) via a serial interface. The inline process control can be realized during the printing process based on trigger points (variables) in the CNC code or faults such as the well-known spaghetti effect can be detected at an early stage after each printed layer [8]. For process planning of the individual process steps (printing, milling, handling, image processing), the MATLAB-based application “HybridPlaner” was developed.. The development of the process planning tool is motivated by the fact that up to now there has been no universal software for hybrid additive manufacturing planning or software that is adapted to the system concept of the 4K FFF system [15]. The HybridPlaner provides the operator with a graphical user interface (HMI) that allows him to interactively plan the manufacturing process with all necessary steps. Once planning is complete, the HybridPlaner automatically generates the corresponding CNC code. This code is then exported and imported into the HybridPlaner, where it is immediately translated from the MARLIN-specific code into a DIN-compliant CNC code. This is followed by the planning of the required imaging, milling and handling processes through a process strategy defined by the manufacturing expert. Each added or planned production step is automatically inserted by the HybridPlaner into the prepared CNC code of the FFF process at the appropriate places. The result of the process planning and output of the

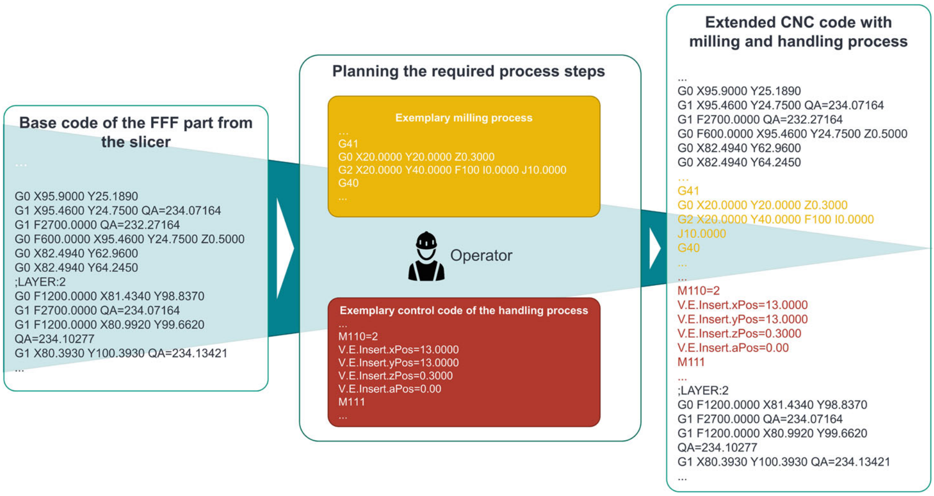

Fig. 3 Basic principle of the extension of the base G-code with the sub-process steps

HybridPlaner is an extended file with the CNC code executable by the 4K FFF system. Figure 3 shows the control code generation in the Hybrid Planner schematically using exemplary code excerpts.

The software helps the user decide which layer of the part to plan a sub-process on by providing a graphical visualization of the individual printing layers and a layer-by-layer display of the CNC code. The actual planning of the various sub-process steps itself takes place in separate, analogously structured program areas. In each of these windows, the user enters all the data required to define the sub-process (geometry, process parameters, machine commands, …) via an input mask, from which the control code is automatically created and displayed for the user on the graphical user interface (HMI). At the same time, the defined sub-process is graphically animated so that the user can understand, evaluate and, if necessary, iteratively adapt the result of his planning. Challenges and limits of the current process chain are:

- Due to the use of three different software tools (CAD, CUR, HybridPlaner), there is still a high manual planning effort.
- Expert knowledge is required for all sub-processes.
- If the manufacturing processes to be planned become more complex, the planning concept of HybridPlaner reaches its limits. If, for example, a complete component contour is to be post-processed with the help of a milling process, the HybridPlaner does not offer the necessary range of functions and the program-side support as CAM solutions available on the market.

- The existing robot module cannot be decoupled from the FFF module due to the prevailing safety logic. In other words, the subsystems cannot be operated separately or autonomously. This has so far made flexible use impossible.

3 Conceptual Process Extension of the 4 K FFF Process

With an increasing shortage of skilled labor, there is an urgent need for flexible and highly automated production systems. In particular, the automated post-processing of FFF parts is nowadays still dominated by manual tasks (loading and unloading of parts in the cleaning bath, painting…). Also in the context of increasing resource efficiency, repairing parts can extend the product life cycle and thus avoid cost- and material-intensive new production. Based on these facts, the existing 4K FFF machine at the wbk Institute for Production Science will be extended in terms of software and mechanics to enable automated repair and post-processing of polymer components. The following points describe the concept of the extended process chain and the intended control architecture.

3.1 Extended Postprocessing Workflow

A modular manufacturing solution will be built for the fully automated mass production of individualized, 3D-printed components. Any combination of the individual steps is possible, as intermediate postprocessing steps can also be realized. A robot kinematic system on a 7th axis serves as the core handling element. Both the multi-material 3D printer described above and a wide variety of post-processing modules can be docked onto this linear axis module with a KUKA KR6 robot (see Fig. 4).

Among other processes, these modules include the following:

- Insert supply and in-process integration by a robot
- Support structure removal using an alkaline or water-based immersion bath
- Optical 3D quality part measurement
- Vibratory grinding for surface smoothing
- Laser ablation

Both the planning of the entire production run and the individual process steps have to be converted into an automatic planning workflow based on the CAD data. As a result, the user should only have to create the CAD model and retrieve the finished, fully post-processed part. The current approach to realizing these concepts is shown in Fig. 4 as a rendered CAD model.

It shows the existing multi-material 3D printer with an integrated milling spindle. It also shows the central handling module with the attached robot. Standardized modules

Fig. 4 Rendering of the extended process chain. A robot on a linear axis is used to transfer the 3D printed parts from the FFF printer module between the various other processing modules

can be attached around this core element. The modules have an electrical connection, compressed air and an EtherCAT connection to the central switch. With a breadboard-like hole pattern on the top plate, various postprocessing machinery can be mounted. A simple storage solution for a variety of grippers or as well as a buffer for workpieces during production can be realized too.

3.2 Concept of the Digital System Architecture

The following Fig. 5 shows the planned control topology.

The challenges and limitations of the previous system described in Sect. 2.2 are to be made possible through a targeted change in the control architecture. The focus of this

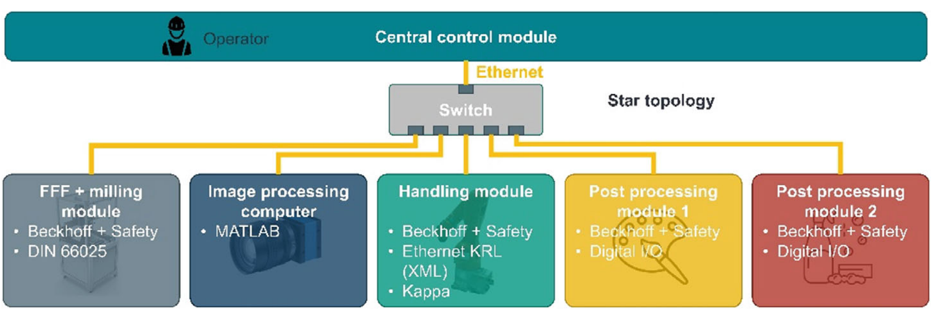

Fig. 5 Control architecture with modules and module-specific structure of the control system

consideration should be a system concept that is as flexible as possible, in which the process chain is configured according to the required process steps.

Topology: In the intended process chain, all systems are connected to a star topology using Ethernet. Starting from the central control module, all subsystems are connected in a star topology using a switch. A major advantage of a star topology is the relative simplicity of expansion and a high transmission rate. In addition, a failure of one component does not lead to a failure of the entire system. Troubleshooting is simple compared to other topologies.

Central control module: The central control module or, in other words, the process control computer primarily forms a human–machine interface to the existing PLSs of the subsystems. Depending on the part and the required process sequence, the relevant production process is to be started and monitored on the connected module. Furthermore, user-friendly planning of the required part-dependent process steps is to be made possible within the central control module and thus the control codes of all modules with required iterations for inline process control are to be generated.

Subsystems: All modules (except image processing) contain their CPU or programmable logic controller (PLC) with the necessary inputs/outputs to process the module-specific tasks. In addition, each module has its safety logic, so that an integrated or autonomous operation can be guaranteed. The control commands of the modules and their sequence of processing are orchestrated by the central control module.

Image processing: The necessary steps for the inline measurement of the components employing a 2D or 3D camera are supported by an external computer and image processing software in MATLAB. The main task of this computer is the processing of the image data including the interpretation of the measurement results and the decision on the further sequence of the process. Such key points are integrated into the control code of the subsystems by the central control module.

Increased system flexibility: Depending on the component, not all modules or subsystems are required. Modules that are not required should be placed in a nearby park or operated autonomously at another location. If it is necessary to connect the modules to form an overall system, the module-specific safety logic must be linked. With the help of the TwinSAFE Loader from Beckhoff, flexible linking of the safety controls via customizing is to be ensured [16]. This means that with the help of a central safety controller (e.g. FFF module), the safety controllers of the other modules are connected or disconnected in a user-defined manner. This way of linking the safety logic ensures flexible and, in particular, safety-compliant operation following the Machinery Directive 2006/42/EG.

4 Use Cases

The following section presents two projects, which are based on the extended process chain. Section 4.1 presents a process chain for automated post-processing of FFF parts. Section 4.2 describes the concept of a process chain for the automated repair or modification of broken components.

4.1 Automated Postprocessing of FFF Parts

Aiming at a fully automated generation of 3D-printed objects using FFF printing technology, the presented concepts are realized in the project *Auto-FFF* funded by the central innovation program for SMEs of the Federal Ministry for Economic Affairs and Climate Action (BMWK). Various use cases demonstrate the bandwidth of necessary processes for the production of additively manufactured parts. These include challenges in the actual 3D printing by adding functionalized structures and additional components. But also, in the subsequent removal of previously required support structures and the finishing of surfaces through processes such as grinding, dyeing or coating.

Due to the high manual effort involved in these very process steps, automation offers significant cost and time savings. Up to this point, the contradictions between individuality and automation have canceled each other out, but 3D printing provides a new and more efficient market for individualized mass-produced products. However, to meet the quality demands of consumers, the finishing processes should also be automated.

Figure 6 shows a total of four different use case parts. The housing components require threaded inserts to fasten other elements. In addition, printed support structures must be removed. A smooth and suitably colored outer surface of the housing is desired. The necessary tolerances for the pin connections must also be complied with. The second use case involves a rounded surface. Here, the staircase effect must be compensated during post-processing to achieve the required tolerances as well as roughness values. In a third use case of an RFID tag, different colored materials have to be printed simultaneously. The RFID electronics installed between the two parts are inserted during the printing process. In the last of the four use cases, a connector adapter is produced in large quantities of more than 2500 units. Due to the geometry, support structures have to be removed subsequently. In addition, a colored coating must be applied. The goal is the continuous automation of manufacturing processes for the ready-to-use production of individualized parts and their handling within the interlinked process steps.

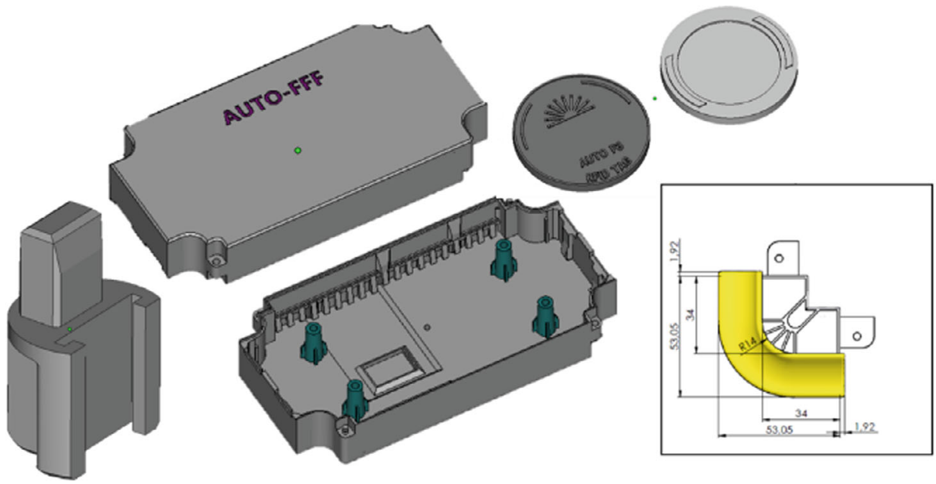

Fig. 6 Collection of parts from various applications with different requirements

4.2 Repair and Modification of Additively Manufactured Parts

The RESTORE project, which is funded by the InnovationCampus Mobility of the Future, has the goal of developing the necessary fundamentals for remanufacturing process chains for functional, hybrid polymer parts. Based on the vision of a sustainable and resource-saving society, which would like to define the long usability of products through a right to repair, the intention is to expand an existing component-flexible machine in terms of hardware and software. In the future, this will enable a high degree of flexibility in the remanufacturing of various components, as the required thermal, mechanical subtractive and additive process steps of the machine will later be defined exclusively via digital process planning. The product to be processed is to be opened, disassembled, repaired or adjusted for the intended purpose by the machine and reassembled for further use (remanufacturing). This remanufacturing strategy offers essential advantages in the context of resource efficiency and reparability. By using the extended process chain, transport routes are eliminated, handling operations are simplified and iterative and combined use of the different manufacturing principles is made possible. Using a highly hybridized polymer component in the form of an adaptable and repairable axial flux machine (AFM), a repair process (e.g. the replacement of a defective motor winding) and a modification process (e.g. insertion of a pole shoe with higher packing density and thus higher torque) are to be demonstrated. Essential research contents of this project are:

- Creation of a development guide for components to be repaired
- Creation of a failure catalog and failure categories
- Enabling the machinery for the repair / modification process

- Derivation of process strategies for damage-minimized disassembly/assembly
- Demonstration of technical feasibility based on the axial flux machine

To analyze and enable the remanufacturing process of the axial flux machine, all process steps are analyzed based on a function plan according to DIN 2860. * MERGEFORMAT Fig. 7 shows the principle sequence of the process chain for the case of the replacement of a defective pole shoe. The axial flux machine is first fed into the process in a fully ordered manner and clamped in place. With the help of a laser process to be developed, a minimally invasive opening of the electric motor is to be achieved. After removing the housing cover, the defective pole shoe is cut out. After the seat of the pole shoe has been prepared (e.g. milling process), the new pole shoe is inserted. Finally, the previously removed housing cover is joined and the complete axial flux machine is assembled. During the entire process, inline process control data will be collected and analyzed so that elements of the AFM are always correctly gripped and handled. The following challenges are to be addressed within the scope of this research project:

- Development of suitable gripping and clamping technology
- Derivation of software-based data processing including all test steps
- Experimental determination of a minimum damage process strategy
- Proof of the technical feasibility of the system (repair and modification process)

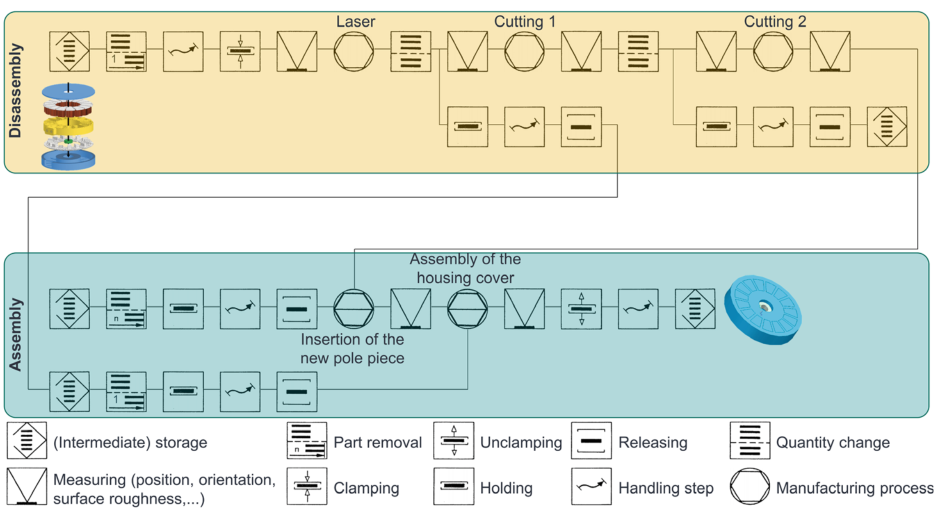

Fig. 7 Exemplary flow chart according to DIN 2860 for the replacement of a defective pole shoe of an axial flux machine

5 Conclusion and Outlook

Additive and especially automated manufacturing of highly integrated components is playing an increasingly important role in today's world. In the context of a growing shortage of skilled workers, increasing individualization and, in particular, the growing right to repair products at the end of the product life cycle, production technology is facing major challenges. In addition to the fully automated production of highly integrated components (Auto-FFF), the automated repair (RESTORE) of components is also becoming the focus of research and development. In two affiliated projects, a fully automated production of FFF components with post-processing and the repair of plastic components are to be made possible in the future based on an existing machine concept with flexible control architecture (star topology). The next steps deal with the implementation of the existing machine concept and the realization of a flexible control architecture.

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