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Quality-oriented production planning of battery assembly systems for electric mobility

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Abstract

Electric mobility seems to be a viable solution for individual mobility in future. However, the use of these alternative drives is accompanied by high costs caused by the battery production. One approach to reduce the production costs is to reduce the rejection rate by integrating appropriate quality assurance measurements in assembly systems. To avoid subsequent, expensive modifications, those measurements must be integrated into the assembly system planning. Therefore, possible integrated measurement technologies for quality-critical characteristics have to be developed and evaluated for the use in the battery assembly. The results are integrated in a planning system to support assembly planners.

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Electric Mobility; Quality Assurance; Assembly Planning

Introduction

Individual mobility is highly important for a constantly growing number of people. For example, from 2000 to 2030, the passenger car density in emerging countries like India, Brasil or Indonesia is expected to increase by more than 400 percent. [1] The increasing demand for individual mobility and thus the need for fossil sources of energy faces several challenges in the future. The worldwide climate change leads governments to implement tighter regulations by reducing pollutant emissions and energy consumption. Also the availability of fossil fuels, that today enable the individual mobility, is limited and only locally available. In consequence, increasing energy costs lead to a strong need for new technologies that enable mobility in future. [2]

Challenges of battery assembly

Electric mobility seems to be a viable solution for these manifold challenges. One the one hand, pollutant emissions can be reduced locally by up to 97% through substituting the fuel consuming engine with an electrical powertrain that mainly uses lithium-ion batteries as energy source. [3, 4] One the other hand, the high manufacturing costs of batteries impede the market success of electrified cars. In order to seriously compete with conventional mobility solutions, the efficiency of battery production has to be increased by improving associated production systems. Especially further developments of battery assembly systems show great potential to improve the situation. [5]

In this context, uncertain market developments caused by unknown political and economic influences prevent the optimization of assembly systems for special sales volumes. Hence, assembly systems for flexible output volumes have to be designed. Furthermore, different existing variants of batteries and a missing standardization of battery designs as well as a great number of usable process technologies prevent assembly systems from becoming more competitive. [6] Modularly constructed assembly systems could provide a solution. [7]

A further impediment of increasing the efficiency of battery assembly is the minimization of the rejection rate. To prevent defective high-value products (the rejection rates of

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single process steps are in part in the high one-digit percentage range) from further processing, capable quality assurance measurements have to be integrated in the assembly processes. This way, safety hazards for workers and future customers arising from defective products can be excluded. [8, 9] In addition, a significant reduction of manufacturing costs by reducing scrap, could lead to achieving the best possible goals of selling electric vehicles at acceptable prices from 11.000 € to 25.000 €. [6]

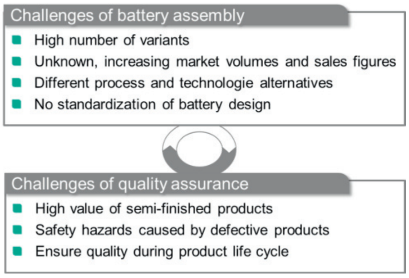

Fig. 1. Challenges of battery assembly and quality assurance

Because of the existing interactions between the product development, assembly systems and quality assurance, those three aspects have to be considered at the same time in the early planning phase (see figure 1). [10] This way, subsequent expensive hardware modifications can be avoided and an optimization of the use of assembly technologies and quality strategies at an early stage may be facilitated. To integrate quality assurance measurements in the assembly planning process, quality methods and measurement equipment have to be evaluated in advance for this application.

Battery assembly process

Regarding a pouch cell battery for electric vehicles, the battery assembly can be divided into the module and the battery assembly. [8, 11] The module assembly starts with extracting and gripping the cells. Depending on the battery module concept, different assembly sequences are conceivable. Usually the cells are stacked, sensors are integrated and their terminals are connected by screwing or welding, which are the currently used manufacturing technologies for this process step. [12] Afterwards, cooling components can be installed. The sensors and connections can be checked by an inline test. After the module housing is mounted, a final check of the battery module is conducted as a final process step. [12, 13] In the battery assembly, several modules are inserted in the lower part of the battery housing, depending on the type of battery. Following the assembling of the contact bars for the modules, the battery management system and the cooling system are inserted and fixed. Also the cells are charged to a desired level. In the end, the battery lid is applied and the battery is subjected to a tightness test. [13, 14]

Quality assurance during battery assembly

Quality assurance during battery assembly always depends on the various types and variants of parts to be assembled, e.g. cells, cooling components and housings and different assembling technologies that need to be taken into account. In fact, the use of measurement equipment for quality assurance that can be integrated in the assembly line (the so-called inline quality assurance the approach focuses on) heavily depends on each special application. [15]

In general, different types of cells and components, which are usually marked by different kinds of barcodes, have to be identified by optical measuring systems like camera systems or laser scanners. Similar systems are used to solve tasks in the area of correct positioning of various components, like cells during cell stacking, or cells and contact bars when connecting by welding. [16] In addition, completeness checks are common tasks for camera systems. Electric measurement devices are used to observe electrical characteristics, like voltage, the state of charge and the internal resistance of cells and modules, and finally to check the characteristics of the entire battery system.

The inspection of joining locations poses the main task to quality assurance systems during the battery assembly. [17] Besides camera systems for position recognition and completeness checks, process parameters like the torque or the turning angle are verified when joining parts by screwing. To detect failures in the welding processes, the parameters of such processes have to be controlled. Failures on the surface of the weld seam can be checked by several optical measurement systems. Different volumetric defects like inclusions or pores that cannot be detected by observing the weld seam surface, have to be excluded by the selection of appropriate welding process parameters that were previously defined by the help of destructive laboratory tests (e.g. tensile tests). [16] The controlling of the transition resistance by electrical measurement devices does not necessarily determine the quality of the joining. Non-destructive test procedures like thermography or acoustic systems first have to be qualified for the use in battery assembly. During the application of glue for glue joints or during the application of heat transfer media, the position and geometric shape of the bead can be measured by camera systems, laser triangulation or a combination of both. In order to check the tightness of the cooling components and their attachments, pressure and leakage tests are carried out. [13]

At the end of the assembly process, software systems have to be checked and electrical characteristics are controlled again as part of the end-of-line test. Also, a possible coating of the housing has to be visually checked. In addition, the dielectric strength of the battery system has to be checked to ensure electric isolation. Visual inspections as well as weight controls for different module and battery components accompany the process all the way. [13]

4. Deficits in quality-oriented production planning

Regarding the planning of assembly systems, several approaches exist to compute a minimum cost assembly line by balancing included assembly processes [18, 19, 20] or choosing ideal product mixes on one line. [21] There are also methods to configure assembly lines by taking product requirements into account. However, none of the approaches mentioned before refer to battery assembly lines in special. Li does refer to battery assembly planning in special, but does not take quality assurance, the modularity of assembly stations or the comparison of different manufacturing methods into account. [22, 23]

In more general approaches, the integration of quality systems into systems is determined after planning and implementing respective processes of assembly systems. [24]

Various quality management methods consider defining quality characteristics during the product development phase [25, 26, 27] and transferring them to inspection schedules [28]. Other methods define the optimal use of test equipment by regarding the overall quality rate of systems [29] through implementing optimal measurement devices. [30]

The optimization of production systems by planning dynamic inspection schedules is a different field of science. For example, the amount of inspections can be determined by the product mix and maintenance intervals. [31, 32]

All in all, none of these approaches consider the integration of quality assurance and appropriate measurement devices in the processes of battery assembly planning. In order to generate added value by regarding quality assurance during assembly and production planning, application specific measurement systems must be qualified and described so that they can be linked to appending planning processes.

5. Development of a configurator for battery assembly planning

To provide a decision support in planning battery assembly lines or production-ready products to operators (product planners and assembly planners), are software tool is needed. For this, based on the customer's and car manufacturer's individual product requirements, the developed configurator delivers an automated configuration of a changeable battery assembly including the necessary quality assurance equipment. Therefore, alternative assembly realizations have to be evaluated and the selection of suitable quality assurance equipment has to be considered at an early stage of the production system planning. [7]

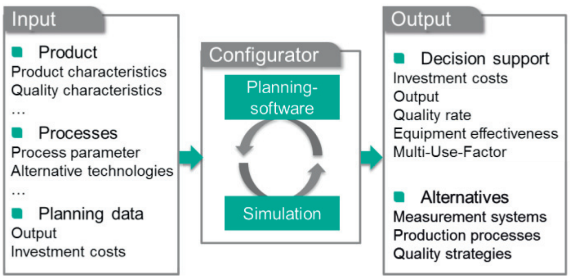

Fig. 2. Configurator for battery assembly planning [7]

The development of the configurator, including the integrated planning method for a battery assembly is divided in the following steps (see figure 2). First, the product, single assembly steps as well as relevant quality characteristics are analyzed. Furthermore, a modularization possibility of assembly stations is examined to later configure an assembly station, which fulfills the individual product requirements. To enable an automated planning of a battery assembly, all interfaces between the product, assembly station modules and quality assurance equipment have to be defined. Afterwards, assembly stations must be configured, using an algorithm that tests the modules‘ compatibility. Additionally, the relevant quality assurance equipment has to be identified. The configured assembly stations and identified quality assurance equipment are inputs for the following material flow simulation. Every existing alternative, defined by the use of alternative assembly stations, is simulated. Different quality assurance strategies, as for example a 100% control or a statistical process control, are implemented for each quality assurance system to test their optimal combination along the whole assembly line. The simulation shows the overall equipment effectivity of the assembly line. The last step is a prioritization of the different assembly lines based on the overall equipment effectiveness, its changeability considering future product developments and needed investments as a decision support for the operator. Finally, all individual sections have to be combined and implemented in an equivalent software concept. [7]

6. Integration of quality assurance in battery assembly planning

A difficulty in generating results regarding the selection of measurement equipment is the missing qualification and evaluation of quality assurance systems, which can be used directly integrated in or between battery assembly processes. Instead of (often destructive) laboratory tests, quality assurance measurements must be conducted inline to allow short control loops and to avoid generating waste by producing deficient products.

In order to solve these problems, the presented approach is structured as shown in figure 3: at first, the relevant quality characteristics of the batteries to be produced and the different characteristics of quality critical processes are identified and transferred to detailed descriptions of the respective measurement tasks. Afterwards, a catalog of relevant measurement equipment is set up considering both, the requirements of the planning configurator and each measurement task. If necessary, new quality measurement equipment must be qualified and adapted for the use in battery assembly. Finally, the qualified measurement systems are connected to the configurator via quality data information modules.

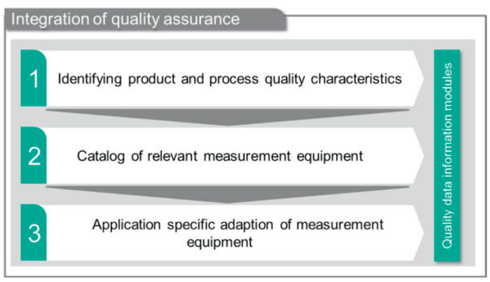

Fig. 3. Integration of quality assurance

6.1. Identifying product and process quality characteristics

The relevant product and process characteristics are assigned to a generic battery and a generic assembly process in order to avoid implementing a configurator that is tailored individually to the design of a special battery variant or exclusive process technologies. Afterwards, a risk analysis of the gathered characteristics is conducted by a team of product and process experts. Therefore, the FMEA (failure mode and effects analysis) is a proven concept to present quality critical components or process steps in detail. [33] The selection area is limited beforehand by a part-function-matrix to reduce the amount of effort. Thereby, the interactions between components and process steps are evaluated and the most affected ones are further investigated. With the help of the FMEA, possible causes or consequences of failures and failures themselves are collected for each process step and identified in the generic assembly process. The result of the FMEA is the risk priority number for each failure. It is calculated by the product of the evaluated probability of failure occurrence, the importance to the customers (equally following the process steps) and the probability of failure detection by actual quality assurance measurements. As a conclusion, quality critical process steps and product characteristics can be identified.

As next step, the risks of significant battery assembly specific tasks during the process steps are described in detail. In contrast to common measurement tasks, the descriptions considered here have to be set up for a wide range of different materials, tolerances and other sub-items. Furthermore, the requirements of the configurator are included in the tasks. For example, possible measurement locations (measurement equipment included in a process or integrated between process steps), as well as the maximum technically permissible weight, the dimensions of the measurement equipment and its environment in the assembly system have to be considered.

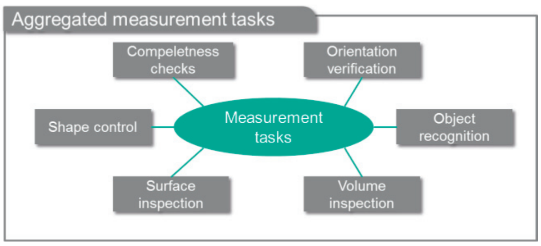

Fig. 4. Aggregated measurement tasks

Finally, different measurement tasks can be summarized to aggregated tasks for quality assurance systems (see figure 4). The aggregation of those quality parameters that need checking provides a basis for a later selection and derivation of measurement equipment. According to [34], measurement tasks and testing challenges can be grouped in object recognition, orientation verification, volume inspection, surface inspection, shape control and checking the completeness.

6.2. Catalog of relevant measurement equipment

As a basis for setting up a catalog of measurement equipment, evaluation criteria to qualify measurement methods and systems are defined first. One the one hand, criteria are derived from the measurement task, on the other hand different process technologies define special requirements for systems to be implemented. For example, process technologies can affect measurement or assembly systems. Cleaning steps or special handling systems should also be mentioned. Also, safety-requirements that are caused by assembly technologies or the maturity of technology influence the choice of appropriate measurement equipment.

Because a standardized design of batteries and their components does not exist,, test samples are developed that represent different battery and process alternatives. Test samples to qualify measurement equipment for numerous applications include e.g. different materials, geometries, surfaces, and production technologies that are used frequently in battery assembly. Again, test samples are grouped for each aggregated measurement task.

The first selection of measurement equipment to be tested is based on application descriptions of measurement methods, which are created within the framework of the approach. These include an illustration of the physical principle and typical applications other than the field of battery assembly. Also, the best resolutions obtainable, a brief assignment to non-destructive or destructive testing (which is to be avoided) and the inline capability are basically recorded. Afterwards, tests with the chosen measurement equipment and the relevant test sample are conducted. A following parameter optimization by experimental design guarantees the best possible results.

In the next step, the results of the tests and investigations are evaluated by the use of a measurement system analysis according to [33] or [35]. Ideally, the analysis represents the conditions related to the battery assembly (e.g. environment, data processing and different workers). The afore-mentioned requirements and criteria of the battery assembly process are considered in parallel. Upon completion of the analysis, the measurement equipment is qualified for its integration in the battery assembly planning processes.

Finally, the qualified measurement equipment is included in a catalog with quality assurance systems that can be considered by the configurator and other assembly planning systems. Like the description of measurement tasks, the measurement equipment catalog is grouped into the aggregated tasks mentioned before: it also contains the necessary information for planning criteria (e.g. maturity of measurement technology or security relevance).

6.3. Application specific adaption of measurement equipment

However, there are very considerable tasks that cannot be resolved by the state-of-the-art measurement equipment. In these cases, it has to be further developed and adapted specifically for the application during the battery assembly. Potential measurement technologies that need to be adapted can be found in the catalog of relevant measurement equipment or in the application descriptions of measurement methods. Afterwards, the unresolved measurement task and the measurement method to be tested are adopted in real battery assembly processes or in a test set-up under realistic conditions to ensure the transferability to battery assembly systems. To optimize the evaluation methods of adapted measurement equipment, comparative measurements with test equipment that can only be used in laboratory or that represents destructive testing methods should be implemented. A better statement about the measuring process qualification can be derived from the comparison of the two measured values (see figure 5).

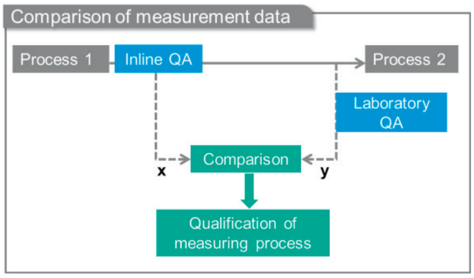

Fig. 5. Comparison of measurement data

After a subsequent parameter optimization, the associated measurement data evaluation is implemented with the aim of enabling graphical analysis. The following measurement system analysis (as described in chapter 6.2) evaluates and qualifies the quality assurance system as a whole for battery assembly.

6.4. Quality data information modules

For the implementation of process-integrated or higher level control loops, the gained quality data has to be prepared conveniently. In addition, a module for the acquisition of measured information, documentation and tracking of each component of the battery has to be defined for the use in the battery assembly. Interfaces, which are already considered in the evaluation phase of quality assurance systems, are finally generated for an alignment with the configurator.

7. Example for adaption of measurement equipment

As a result of identifying quality-critical product and process characteristics during assembly processes, joints in general (either welded joints or bonded joints) have a critical impact on the quality of battery systems. To ensure an ideal surface and position of the joint and supplied materials, optical measurement methods like camera systems or laser triangulation are state-of-the-art and already in use. However, no qualified quality assurance system has been found that is– able to detect non-destructively volume defects in joints (inclusions or pores) inline or integrated in joining processes.

Referring in special to bonded joints, unidentified air inclusions can lead to imperfect joints that could induce an inconsistent strength, leakage, corrosion and no security during the long life-cycle. Since the joining process cannot be reversed, defects should be detected by testing the tightness, to avoid flawed value added processes. The application descriptions of potential measurement equipment have shown that ultrasonic methods or thermography could be able to detect air inclusions in glue beads.

For evaluating the mentioned measurement methods, a test-sample has been created, that covers the most frequently used geometries and materials of glue beads. Defects are included as well. As next steps, an experimental set-up has been designed to test those measurement methods. First results have shown that ultrasonic methods in special can be able to detect air inclusions in glue beads during the application.

As following steps, the two measurement methods (if capable) are integrated in a bond joining process that simulates battery assembly conditions. Therefore, the sensor to be used has to be added to the applicator and herewith the sensor has to take movements of the robot that handles the applicator into consideration.

Before evaluating the measuring process by a measurement analysis, a suitable measurement data analysis has to be implemented which is able to detect air inclusions and to provide the gained quality knowledge to control loops. When evaluated as capable measurement equipment, ultrasonic sensors or thermography can be integrated in the catalog of relevant measurement equipment for battery assembly.

8. Conclusion

There are different deficits in the planning of the battery assembly for a quality-oriented system. Especially the consideration and integration of quality assurance systems in the very early assembly planning phase presents several challenges. With the help of the presented approach, quality-critical product and process characteristics can be defined and appropriate quality assurance systems can be derived and described in a measurement equipment catalog. A planning supporting configurator can integrate the quality assurance systems listed, because its requirements are taken into account when qualifying existing and adapting new measurement equipment. Finally, by this approach, the competitiveness of batteries can be improved and serve as serious solution for individual mobility.

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