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Quality Management for Battery Production: A Quality Gate Concept

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Abstract

Recent scandals in pollutant emissions by combustion engines have once more raised awareness of the relevance of shifting individual mobility to electrically driven vehicles powered by renewable energies. High costs and large quality fluctuations during the production of high-energy batteries are considered to be among the main impediments of electric cars to succeed on the consumer market. In order to reduce costs and improve the quality of lithium-ion batteries, a comprehensive quality management concept is proposed in this paper. Goal is the definition of standards for battery production regardless of cell format, production processes and technology. A well-structured procedure is suggested for identification and handling of fluctuations in the quality of intermediate products, leading to a reduction of scrap rates by detecting deviations in early process stages and, additionally, offering the possibility for process control and feedback. Based on a definition of internal and external requirements for processes and intermediate products, the relevant parameters are derived and requirements for measurement equipment are identified. By establishing internal decision points (quality gates), measurement steps can be aggregated, minimizing effort for quality control and summarizing information on relevant quality parameters of intermediate products. Hence, recommendations for process control and the definition of rejection criterions and classifications for intermediate products are provided.

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Keywords: electro mobility; production engineering; quality management; lithium-ion batteries

1. Introduction

The ever increasing demand for individual mobility enabled by the success of the internal combustion engine has led to a sharp rise in carbon dioxide and pollutant emissions, resulting in severe ecological and social hazards, such as global warming, smog and noise pollution. Car manufacturers have been struggling to comply with emission limits, resulting in one of the most severe fraud scandals in the recent history of automotive manufacturing [1]. Electrically driven vehicles are emission free during operation when charged with electricity generated by renewable energies. High cost, low range and safety concerns mainly caused by the electrochemical storage device have hindered successful market positioning on a large scale so far [2]. In the near future, one of the main challenges will be to reduce manufacturing costs of batteries by numbers of scale and experience in battery production [3]. Due to their large energy and power density, lithium-ion batteries are among the most promising solutions for the application in electric vehicles (EV) [4]. Although lithium-ion batteries have become well established in consumer electronics, there are several challenges yet to be overcome for batteries in electric vehicles. Among these are quality requirements, such as safety and lifetime, as well as difficulties in the production of large-format high-energy batteries due to size, handling and testing [5,6]. While, before shipping, consumer cells are usually only charged until the solid electrolyte interface (SEI) has formed, batteries for electro mobility are subject to intensive testing. This causes immense financial and logistical effort due to expensive testing equipment and long storage times [7,8]. In order to reduce back-end testing and minimize quality fluctuations in high-value products, quality assurance in early production stages has to be implemented. Although several approaches have been presented for quality assurance of single production processes [9-13], a comprehensive method for quality management during the production of lithium-ion

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batteries has long been overdue. In order to investigate product and process interactions for the whole production chain, the high-energy battery cell production research center has been implemented at the Institute for Machine Tools and Industrial Management (*iwb*) at Technical University of Munich, covering the whole process chain for the production of large-format lithium-ion batteries. A product and process model for production system design and quality assurance for EV battery cells has been developed [14] and methods for quality parameter identification and classification in battery cell production [15] and complexity management for the start-up in lithium-ion cell production [7] were presented. Based on this groundwork, the presented paper will focus on quality control during the operation of the process chain for lithium-ion cell production.

The paper is structured as follows: Fundamental properties and production of large-format lithium-ion cells will be briefly explained in section 2, followed by a review on quality assurance in battery production, a summary of methods for quality management during the operation of complex production chains and an overview of quality gates in production processes in section 3. Subsequently, in section 4, a comprehensive method for quality management using quality gates in the production of lithium-ion cells is presented in order to reduce cost and increase quality of lithium-ion cells.

2. Characteristics of battery production

2.1. Production chain for lithium-ion batteries

Lithium-ion cells are galvanic elements that convert electrical energy into chemical energy and vice versa [16]. Hence, they are able to store and release large amounts of energy, e.g. electricity generated by solar or wind energy used to power an electric vehicle. They generally consist of two opposing electrodes and a transfer medium (electrolyte) which enables the flow of positively charged lithium-ions from one electrode to the other, as well as a separator to electrically isolate the electrodes and electric contacts to enable electron transport via an external electric circuit [3]. A detailed product model for lithium-ion cells was presented by [14]. Most common formats cover cylindrical cells, prismatic hard case cells and pouch cells.

The production of lithium-ion cells has a big impact on cost and quality of the batteries [3,17]. A detailed description of the production chain for lithium-ion cells can be found in [4] and [14]. The production chain can be subdivided in three phases, i.e. electrode production, cell assembly and formation. Electrode production mainly covers process engineering disciplines, such as mixing of the active materials, coating of the anode and cathode materials on copper and aluminum foil, drying of the electrode foils and compressing of the electrodes. Cell assembly is dominated by manufacturing and assembly technology. Here, the anodes and cathodes are preconditioned by slitting, punching or cutting, before cell stacks are generated by winding, stacking or folding of anode, separator and cathode foils or sheets. After packaging, the cells are filled with electrolyte and stored until a homogeneous dispersion of electrolyte in the cell is achieved. The last steps in cell production are mainly covered by electrical engineering, the most important step being the formation. Here, the cell is charged for the first time and the SEI is formed, which is crucial for the later performance of the cell [16]. Afterwards, lithium-ion cells for EVs are subject to intensive testing and aging procedures for quality classification.

2.2. Characteristics and requirements for quality control in battery production

A multiplicity of engineering disciplines, e.g. process engineering, manufacturing and assembly technology, as well as chemical and electrical engineering is involved in the production of lithium-ion cells [15], combined with a large variety of process alternatives, depending on cell format, cell design and manufacturer [18]. As deduced in [15], the production of large-format lithium-ion cells fulfills all basic characteristics of complexity [19]. Among these are the multiplicity and variety of processes and relations between process steps and intermediate products, a large diversity of cell manufacturing processes, mostly unknown and ambiguous interactions of process parameters and intermediate products, as well as a partial time-variability of processes and relations. This complexity, in combination with a lack of standards in geometry and design, as well as unknown requirements for quality assurance and production environments, e.g. technical cleanliness, has led to an over-engineering by machine manufacturers due to unknown requirements, high scrap rates during cell production and extensive testing procedures before module assembly [7]. The introduction of new material combinations to increase quality parameters such as safety, energy density or lifetime of the cells [20] will make a comprehensive quality management for EV battery cell production inevitable, covering not only the start-up, but also the operation of the whole process chain, independent on cell format, production processes and technology.

Hence, a comprehensive method for quality management during the production of lithium-ion cells must be capable to meet the following requirements:

- process collected data for process control and feedback in real time,
- while covering the complexity of the production chain as well as the interactions and correlations between process and product parameters and
- decoupling interacting processes and aggregating information to enable decisions in case of target deviations.

In addition, quality control during production must be economically feasible and, therefore, expenses for measurement and necessary rectification must underprice those for back-end testing and defective end products. A standardized procedure for identification and handling of fluctuations in the quality of intermediate products, as well as documentation to comply with customer requirements would be desirable.

3. Literature review: Quality management for complex production chains and battery production

3.1. Quality assurance in battery production

Several approaches for quality assurance in battery production concerning single processes have been presented in literature, such as the analysis of defects during electrode coating [9], the optical detection of particles on the electrodes after preconditioning using a photo-optical camera system [10] and online detection systems in separator manufacturing [11]. A tolerance design method for electrolyte mixing processes based on statistical design of mixture experiments was presented by [12].

Only few publications in the field of battery production focus on comprehensive quality management concepts. A method to describe the process capability for multiple stable processes was presented by [21] for the manufacturing of lithium-ion battery protection integrated circuits. A tool for quality-oriented production planning in assembly of battery modules was developed by [22], defining critical product and process characteristics and deriving appropriate quality assurance systems using a measurement equipment catalogue. This approach, however, only focusses on the assembly of modules, disregarding the complex cell production process. A comprehensive quality management concept for the start-up of the production chain for lithium-ion cells is presented in [15] and [7]. None of these approaches, however, cover the above stated requirements for the operation of the process chain during lithium-ion battery production, particularly the real time processing of data in a complex production chain.

3.2. Quality management for complex process chains

Due to the complexity of the production chain for lithium-ion battery production, classical tools of quality management in production, such as statistical process control (SPC), process capability indices and design of experiments (DoE) soon reach their limits of applicability [15]. Quality management for the operation of complex process chains has been subject to investigations in a large variety of publications. Here, only a short overview of the most important works in the field of quality management for complex process chains will be summarized. For further details and a comprehensive overview, see [15]. A systematic concept for quality oriented optimization of complex production chains was validated for final assembly of airplanes and production of solar modules in [23]. The concept presented by [24] focusses on feedback loops for production chains, while [25] provides a method for failure based optimization. Further concepts for production chain optimization were presented by [26] and [27]. In order to determine quality relevant cause-effect relations, an approach for the application of modelling and analyzing techniques of novel technological process chains was presented in [28]. A comprehensive concept for the integration of quality measurement and quality planning was developed in [29]. However, none of the approaches presented above are applicable to a complex and heterogeneous production chain covering process engineering, manufacturing and assembly technology as well as electrical engineering, while decoupling interacting processes and enabling real time control of production. Hence, a comprehensive quality management method for lithium-ion cell production is required, being able to cover all the challenges summarized in 2.2, independent of engineering discipline and technology.

3.3. Quality gates for production processes

Quality gates, as presented in the stage-gate model [30], are nowadays a wide-spread quality management tool in product development and project management, i.e. in the automotive sector [31]. They have been shown to be applicable to a large variety of processes and process chains, enabling a comprehensive control of quality relevant features [32,33]. Although initially proposed for the use in product and software development, an adapted stage-gate model has been shown to be applicable to support quality management for production systems, especially in the context of zero-defect manufacturing [34]. While in strategical planning and development processes, a strong focus is on the consequent application of quality gates for control of process results, quality gates in production and assembly processes focus on control of process parameters [35]. In contrast to classical milestones, which typically are set up as rigid deadlines and, thus, are easily “overrun”, quality gates claim a strong focus on content, maintaining flexibility and condensing project or process results in a well-defined, standardized procedure [36]. Their universal application implies further advantages, such as process data for benchmarking, description of interface contents and documentation for know-how transfer, external partners and certification [35].

The installation of a quality gate system requires a detailed analysis of the corresponding process chain. Measurement steps are set up after selected process steps, in order to reduce scrap rates by detecting failures and deviations in early production stages [35]. Quality gates are control and decision points, offering the possibility for backward and forward feedback loops in production process chains [34,37]. However, the installation of such an interactive control system for a complex interconnection of production processes will easily lead to a rise in complexity and disturbance of the actual production [35]. While enabling prompt troubleshooting by early detection of failures and deviations in production, the application of quality gates for complex production chains yet needs to be demonstrated.

3.4. Conclusion and need for action

As deduced in the previous sections, none of the presented approaches for quality management in complex production chains sufficiently cover the requirements for quality control during the operation of the production chain for lithium-ion cells. A comprehensive quality gate concept can represent a powerful tool to ensure highest quality and reduce effort for measurement and testing by early detection of target deviations while enabling real time process control and providing a standardized communication tool for a multiplicity of engineering disciplines. Particularly with regard to the complex interactions and interdependencies of processes and intermediate products, further investigations are required. Hence, a modified quality gate approach for quality management in lithium-ion cell production is presented in the following chapter.

4. Quality management for battery production: A modified quality gate concept

4.1. Method for quality management in battery production

In order to reduce costs and improve the quality of lithium-ion batteries, a modified quality gate concept is proposed for quality management during production. This procedure can be used for identification and handling of fluctuations in the quality of intermediate products, regardless of technology, cell format and process structure. Hence, by detecting deviations in early process stages, scrap rates can be reduced and process control and feedback are facilitated.

Starting point is an analysis of the corresponding production chain, followed by a definition of external and internal requirements for processes, intermediate and final product properties. Among the external requirements are quality features defined by the customers, such as safety, geometry, performance or lifetime of the battery cells [15]. Internal requirements are intermediate product properties influencing subsequent process steps and intermediate products, but also parameters like process and waiting times, technical cleanliness or dryness. Having defined these internal and external requirements for processes and intermediate products, the relevant parameters influencing the quality of intermediate products and the final cell can be derived. Foundation of this procedure is the method for quality parameter identification and classification in battery cell production presented in [15], which will be roughly outlined here:

A modified failure mode and effect analysis (FMEA) is used to gather expert knowledge on quality and production relevant process-product-correlations. It is based on a definition of the production chain, including a description of all process steps with process parameters and disturbance quantities, as well as a product structure with the corresponding intermediate products, as deduced from [14]. This procedure results in a data basis consisting of process-product-interactions and the corresponding severity, probability and uncertainty values. The information provided covers effects and interdependencies between failure causes. Further steps were presented in [7], using a method based on multiple domain matrices, including Pareto analyses and design of experiments (DoE) for the classification and selection of quality relevant parameters. This procedure can be used to optimize production during ramp-up and provide basic information for quality assurance during production. For the optimization of the production chain during production real time processing of the information is needed.

4.2. Quality gates in battery production

Based on the procedure described above, relevant measurement steps and requirements for measurement equipment are identified. Depending on process layout, accessibility and measurability of product and process parameters, as well as the corresponding measuring effort, following options have to be considered:

- destructive or non-destructive measurement,
- on-line, in-line or off-line quality assurance,
- 100% inspection or randomly chosen samples.

In order to minimize production disruption and waste during measurement, non-destructive on-line or in-line quality assurance is to be preferred where possible. As suggested in [7], a quality gate concept can be installed to subdivide the production chain and aggregate measurement of the relevant process parameters and intermediate product properties, illustrated in Fig. 1.

For the positioning of quality gates, the corresponding production chain has to be carefully evaluated. Some universal suggestions can be made to support the positioning decision [32]. In particular, these are interrelations of processes, added value of subsequent process steps, processes known to be susceptible to errors, identification of a failure source during production, accessibility and measurability of parameters, as well as the process layout.

These quality gates contain information not only on subsequent process steps, but also on correlations between processes and intermediate products over several process steps, as depicted in Fig. 2. This aggregation of information enables a decoupling of processes in order to facilitate a decision on production progress in the case of target deviations. Hence, recommendations for process control and the definition of rejection criterions and classifications for intermediate products are provided.

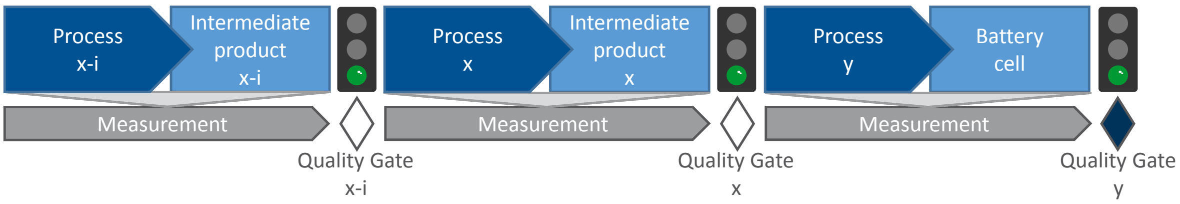

Fig. 1. Quality gates for the production chain of battery cells, aggregating measurement of the relevant process parameters and intermediate product properties.

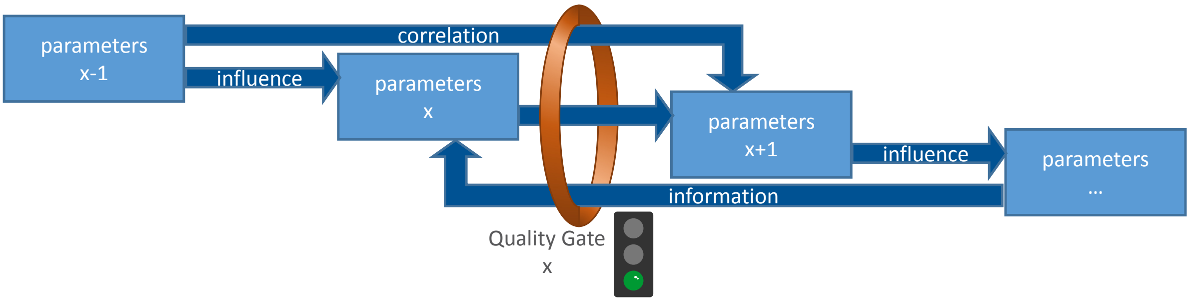

Fig. 2. Aggregation of information in quality gates for decoupling of process steps and facilitation of decision making in case of target deviations.

4.3. Intelligent quality gates

As described in section 3.3., the installation of an interactive quality gate system for a complex interconnection of production processes can result in a sharp increase of complexity and disturbance of the actual production [35]. As shown in Fig. 3, an iterative procedure is implemented in order to control and adapt the number and content of quality gates along the process chain for lithium-ion cell production. The identified parameters and interactions derived in [15] and [7] can be used to set the first number of quality gates and define their content. By a collection and evaluation of the measured data, new information on parameters and interactions can be generated. This information can in return be used to reset, reduce or increase the number of quality gates, as well as their content. Applying data mining methods for real time processing, the collected data can be used for feedback loops, facilitating process control and production chain optimization.

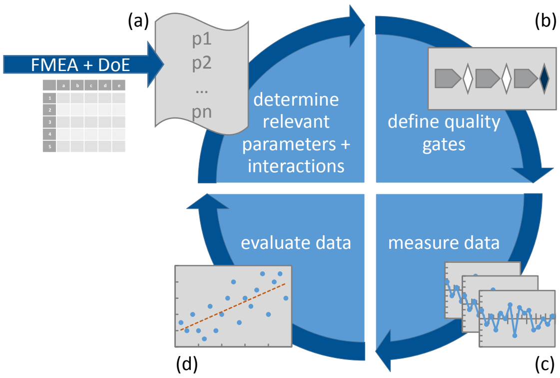

Fig. 3. Iterative procedure for the adaption of quality gates.

As depicted in Fig. 3 (a), the first step for an intelligent adaption of quality gates is the determination of quality relevant parameters and interactions. In the first iteration, process parameters, intermediate product properties and corresponding interactions are determined as described in section 4.1 using a modified FMEA and DoE for quality relevant parameter identification and classification [15]. This information can be accumulated in a matrix based form, e.g. as presented in [7], and stored in a data base.

For the subsequent definition of quality gates shown in Fig. 3 (b), a top-down procedure is applied using the data generated in step (a), dividing the production chain into subsections and condensing measurement steps as illustrated in Fig. 1. Criterions can be specified e.g. in digitalized checklists. As pointed out in Fig. 2, the content of quality gates includes all relevant correlations, influences and information from preceding and subsequent process steps, which must be aggregated in order to enable a decoupling of interacting processes and manage the complexity of the production chain.

During production, as shown in Fig. 3 (c), the relevant parameters are measured and collected in a data base, using in-line or on-line measurement wherever possible. In early production stages, an intensive quality control can be advantageous in order to stabilize processes and gather information on disturbances. Once production runs stably, measurement effort can be reduced in order to lower cost for quality assurance, as will be explained in the following step.

As illustrated in Fig. 3 (d), a real time evaluation of the collected data is carried out, comparing pre-defined requirements and criterions of external and internal customers with the measured data [35] and sending feedback to preceding processes. Data mining methods can be employed to reveal previously unknown correlations and consolidate or refute the findings of [15] and [7].

Hence, an analysis of the obtained information can lead to a revision of the parameters and interactions defined in Fig. 3 (a). Conclusions can be drawn to rearrange the positioning, number and content of quality gates correspondingly, which enables an interactive and self-optimizing control system for quality management in lithium-ion cell production. Due to their universal applicability to a large variety of processes and process chains, as well as the possibility for real time control during production, quality gates can be a powerful tool to reduce the cost and enhance the quality of lithium-ion cells for electro mobility.

5. Summary and conclusion

High costs and large quality fluctuations during the production of lithium-ion batteries are some of the main impediments for the success of electric vehicles on the market. It has been shown that current quality management tools easily face their limits when applied to the production chain of lithium-ion cells due to its complexity and the need for real time processing of collected data. Hence, a comprehensive quality management concept is proposed, using a modified quality gate system for the operation of cell production. This method enables prompt feedback and process control while covering the complexity of the production chain. By decoupling interacting processes and aggregating information on relevant parameters and correlations, decision making is facilitated in case of target deviations. Therefore, effort for quality control can be minimized while maintaining a high level of quality. The concept presented in this paper represents the current state of research and will be implemented at the high-energy battery cell production research center at the *iwb*. A quantitative financial evaluation will be subject to further investigations.

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