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Analysis of Possible Reductions of Rejects in Battery Cell Production during Switch-On and Operating Processes

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Battery cell production is one of the key industries for electric mobility. To become more competitive and economic, battery cell production requires maximum efficiency in every process step. An efficient production can be achieved by a low rejection rate during switch-on and operating processes. For all process steps of battery cell production relative rejection rates and absolute scrap amounts are analyzed. Herein, it is aimed to find out to what extent existing quality inspection systems can eliminate battery cell production rejects, whether there are deficits in their application and if approaches of Industry 4.0 can offer solutions. The results are that coating is the process step with the highest reject and data-driven methods are suitable tools to reduce the rejection rate in the production of current and future battery cells.

1. Introduction

The sales for electric vehicles (EVs) are rising and it can be expected that by 2040 about 70% of all vehicles will be electric.[1] For traction batteries, the battery cells are responsible for 40–70% of the battery pack's value.[2] The growing demand for battery cells cannot be met by the domestic market as there are currently no large-scale battery cell production facilities in Europe. In 2018, only 1% of the EV batteries were supplied by European companies.[1] Thus, German car manufacturers are dependent on cell suppliers from Asia as globally relevant cell manufacturers are almost exclusively located there.[3] Currently, the manufacturing costs for battery cells in Germany are high, and there is still a lack of cell manufacturing experience. Increasing efficiency in production is a possible way of establishing a successful battery cell production and launch the first mass market EVs.[4] Today, the production of battery cells for electric cars has a high rejection rate.[5,6] Therefore, the yield optimization is paramount for battery cell production plants to be operated economically and to find the most cost-efficient plant size.[7,8] The rejection rates of some single process steps are even in the high one-digit percentage range. To reach high production efficiency, it must decrease below 1%. First, the need for research is to evaluate the exact rejection rate in each process step. Second, it has to be determined where rejects occur in battery cell production. The third and final investigation is on existing methods and procedures to reduce the rejection in cell production.

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2. Experimental Section

2.1. Hypothesis

For this study, the following hypothesis is formulated: "Industry 4.0 methods make it possible to improve switch-on and operation processes and thus effectively minimize rejects." The term Industry 4.0 is defined by the German government aiming to achieve a more flexible and efficient production that combines highly complex virtual systems based on cyber-physical production systems and smart factories.[9,10] The methods in this study were technologies that enable the state-of-the-art battery production to reduce scrap. The hypothesis and subhypotheses are evaluated by the selected experts.

2.2. Survey

First, the hypotheses were transformed into questions that both proof the core message and the affected production aspects. Prior to the evaluation the questionnaires and the selected participants were proven for the quality criteria of validity, reliability, objectivity, representativeness, utility, economy, and reasonability.[11] The right data and information were requested—valid. A repeatability for the answers of the requested information was ensured—reliable. The interviewee's answers were independent from the interviewer—objective. The answers could be generalized—representative. There was a gain in insight for interviewees in participating—economic. The duration of participation was acceptable—utility. Finally, the participants had to work at relevant battery branches—representative. For these reasons, each expert was invited personally with regard to his background.

The evaluation of the study was based on 250 questionnaires sent out to experts from industry and research. Each expert could answer a maximum of 23 questions in this study. About 220 questionnaires were returned incomplete because the requested information was too confidential or not known to the experts. Questions concerning the overall equipment effectiveness (OEE) of a plant were usually considered as confidential. Data on reject correlate with the OEE as this was the product of the so-called quality factor (rejects), an availability factor and a performance factor.[12] In addition to the partly incomplete, there were 30 complete filled out questionnaires returned. Consequently, the validity of these answers was high. Slightly more than a quarter of the overall respondents worked at research institutes (28%), a fifth (21%) each at automotive original equipment manufacturer (OEM) and plant manufacturers. The remaining respondents worked in management consulting as battery system and battery cell manufacturers (14%) or as engineering service providers. Referring to the branches, the majority of respondents worked in product development (38%). A further 17% of the participants worked in the field of production. The remaining participants are from the areas of production planning, purchasing, sales, and other departments. For the results, we used the 30 complete answered questionnaires as they are most valid and the additional 190 questionnaires were used when answers were given. For the results in Figure 2, the total number of answers was included.

In the context of this study, "reject" was defined as a product or part of a product which cannot be used for the intended purpose. The start of production (SOP) was the approval of the plant to produce customer-ready products and this study referred only to these already approved plants for small-scale and large-scale production.[13] There was the possibility of rejects occurring along the entire manufacturing process. Test, start-up, and warm-up parts, which were defined in the process planning and were scrapped, were not considered as rejects if these parts could be identified separately in the production process. Rejects often occurred because of the low-quality output of the production processes.[14] These production errors caused reworking or rejects as a subset of the six big errors. The rejects could be divided into three error types. The first were production errors, machining errors, or in-house transport damages. Second, there were rejects that were caused by the delivery of faulty materials, components, or preliminary products that passed the inbound check because the investigated sample was alright. Third, there was unavoidable reject. Rejects were to be understood as unavoidable if they are part of the process such as waste during separation.

"Switch-on losses" were often a major driver of production rejects. Switch-on processes existed not only at the first switch-on of a production facility. Rather every switch-on of the production line generated switch-on losses for example at a start of a shift. During switch-on rejects occurred for instance at the coating process in battery cell production. The layer thickness was not immediately as thick as specified, accordingly, the initial part of the carrier film with too thin or variable thickness was rejected as thickness correlated with variations in the electrode capacity and affected the state of charge during cell tests.[15] In the context of this study, "operating losses" were defined as parts of products which did not yet have their intended product requirements after the machine had been turned on and the switch-on process had been completed.

The three focused "production scenarios" were the lab series, the small-scale production, and the large-scale production. The lab series was defined as a plant with less than one MWh/a production capacity. For the small-scale production, a capacity of more than one MWh/a and less than 1 GWh/a was defined. Production sites above 1 GWh/a were defined as large-scale production and were known as efficient plant sizes.[8]

For all process steps of the pouch cell production in **Figure 1**, the scrap is evaluated with differentiation between the reject in both the switch-on and operation mode as well as in regard to the mentioned production scenarios. For the reason, that OEE was not a complete overall manufacturing performance (OMP) measurement system possible solutions to identify and to omit scrap with data-driven Industry 4.0 applications were evaluated by the experts.[16] The primary-considered methods were continuous improvement processes (CIP) or Kaizen, Six Sigma, Total Quality Management (TQM), and Process Audit.[17]

3. Results

In the following, the study along the process steps of the pouch cell production in reference to the hypothesis will be described. The production process is divided in the three manufacturing sections of electrode production, cell assembly, and the

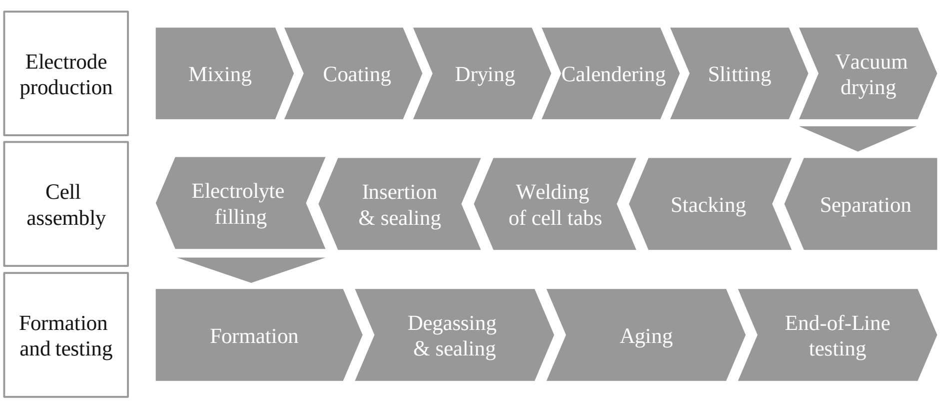

Figure 1. Pouch cell production process of electrode production, cell assembly, formation, and testing.

formation and testing.[18–20] The electrode production section contains the process steps mixing, coating, drying, calendaring, slitting, and vacuum drying. The produced electrodes are separated, stacked, tab welded, inserted in the pouch foil, and sealed for the electrolyte filling in the section of the cell assembly. The activation of the battery cells is carried out in the section of formation and testing accurately in the step of formation followed by the degassing and sealing, aging of the cells, and the end-of-line testing.[21]

The importance of rejects in cell production in general is the first issue. The evaluation of the study shows that 82% of the respondents consider rejects to be "important" or even "very important" in production. For the lab and small series (< 1 GWh/a), about two thirds of the experts say that switching on the line is the main cause of the production reject. For plants with more than 1 GWh/a production capacity, the majority of the experts (60%) say that most of the rejects are caused by the operating losses, as shown in **Figure 2**.

Consequently an interval question is applied where the experts have to select a scrap range of 20% to derive the scrap ratio of switch-on losses in the different production scenarios.[22] The range of the scrap ratios of the interval in question is equidistant.[23] The majority of respondents suspect that more rejects are caused by switch-on losses in small-scale production. For 42% of the experts, 40–60% of the total rejects in small-scale production is due to switch-on losses. A further 35% of experts accuse switch-on losses for 20–40% of the total rejects. About 15% of the experts even see 60–80% of the total rejects as being caused by switch-on losses in small-scale production. Thus, it can be summarized that 57% of the experts see switch-on processes responsible for at least 40% of the total rejects in small series. The situation is slightly different in large-scale production. There, a large proportion of the experts (50%) see only less than 20% of the total rejects caused by switch-on processes. A further 19% each select the scrap ranges 20–40% and 40–60%. It can therefore be derived that in large-scale production, switch-on losses are not seen as the main cause of rejects but are still necessary to focus on. Concerning the introduced process steps in Figure 1, the participants can select five process steps where they assume the most scrap occurrence. The result is shown in Figure 2, where 68% of all experts name coating the process step with the highest amount of scrap. In addition to coating, the stacking process contains high reject assumed by 44%. The third to the fifth worst-rated process steps are mixing, slitting, and electrolyte filling. The process step at which the experts expect the lowest rejection rate is vacuum drying as it can be excluded when it is considered as a buffering or clock time-independent process step. Excluding vacuum drying, aging, and degassing/sealing are the process steps causing the lowest reject. For the trend line, a fourth-degree polynomial curve was chosen to find the best balance between a visible trend and a high coefficient of determination, which in this case is 25.05%. The trend line can be split up into three discrete intervals representing change of impact of a production level on productivity. Considering the overall declining trend of having lower scrap rates at higher levels of product integration is positive from economic perspective.

The absolute deviation of the scrap rates distribution in the process steps is addressed by the survey with the question of how much rejects can be expected from certain process steps. The process reject evaluation of the experts is shown in Figure 4. In this figure, the reject ranges derived from prior expert interviews are displayed on the vertical axis for each process step listed on the horizontal axis. The third dimension of this graph shows the relative number of experts that select the reject range with a circle of increasing diameter. The maximum of expert votes for the rejection rate of each process step is displayed with a filled circle and the percentage attached. To derive a representative result, the median for grouped data[24] is calculated and included in the graph. As with the previous relative distribution of the rejection rates in **Figure 3**, coating is also the process step with the highest rejection rate in absolute terms. No other process step than coating is expected to produce more than 2% scrap (assumed by 52.3%). In contrast, for the stacking process only 23.8% of the experts suspect a rejection rate of more than 2%, although this process step is placed second concerning the relative rejection rate in Figure 2. The experts also expect high rejection rates for electrolyte filling and calendaring. More than 5% rejects are expected by 13.6% experts for electrolyte filling and by 14.3% experts for the calendaring process. In contrast, over 85% of the experts expect a maximum of 1% or less rejects

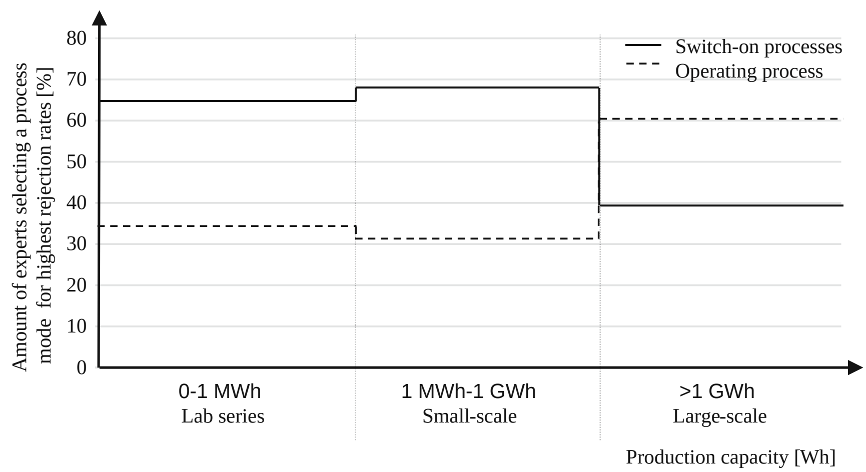

Figure 2. Deviation of reject rates in switch-on and operating process at three scales of production plants.

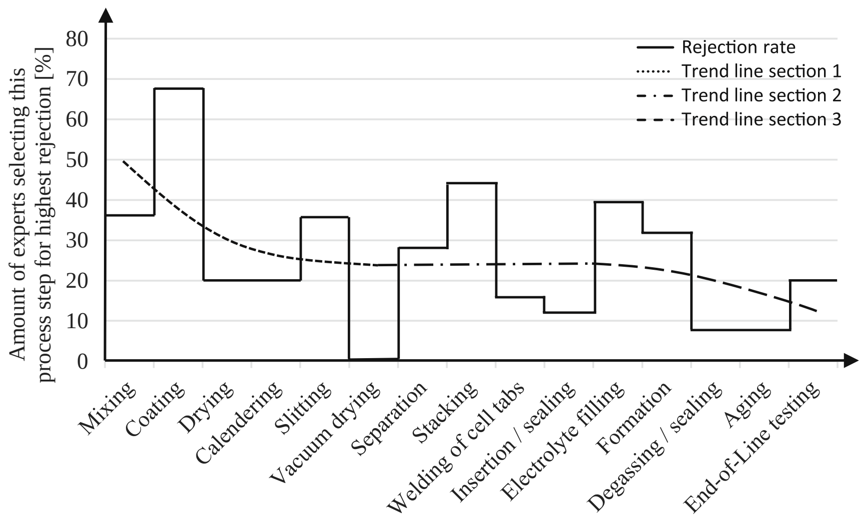

Figure 3. Amount of expert votes for a process step as the most reject causing in cell production.

during insertion and sealing. For degassing and sealing process step the result is obvious. More than 90% of the respondents expect a maximum of 1% or less rejects for this process steps. Two thirds of the respondents expect less than 0.1% rejects in the vacuum drying process step. This is the absolute highest number of expert votes for the reject range below 0.1% resulting in the best performing process.

3.1. Cause–Effect Relationships

Battery cell production is a linking of complex production processes showing strong dependency between all process steps as cause–effect relationship (CER).[25,26] These relationships result in unknown influence on product quality.[27] Interactions can be multidimensional (several effects on one cause) or interlinked (one effect is the cause of another effect).

Concerning the avoidance of rejects by a full understanding of all interdependences, a two-faced result is detected when the experts had to set a mark on a ramp from zero to 100 percent. About 71% of the respondents expect a minimization of the total rejects by more than 45%. The peak value is the assumption of over 83% reject minimization. Contrary, the other 29% of the experts expect only small reject minimization by a maximum of 30%. The median of the individual responses is 50%, the mean 50.04%. The most frequently chosen numerical value or mode is 50% (four times). The distribution shows that the experts either trust the holistic understanding of the CERs to have a clear minimization of rejects or hardly see any potential. None of the respondents chose values between 30% and 45%.

The question of the quality assurance procedures that are suitable for identifying CERs in an Industry 4.0 battery production is shown in Figure 5. The experts are allowed to select more than one quality assurance procedure. Over 69% of the experts consider continuous improvement processes (CIP) or Kaizen to be a suitable quality assurance procedure. After all, almost 60% believe that Six Sigma is capable of identifying the CERs in battery production. Total quality management (TQM) and process audits are defeated by less than 50%. About 3% of the experts have the opinion that none of the quality assurance procedures mentioned is suitable for the required task. Another suitable process named by one of the respondents is process analytical technology (PAT).

One of the most important questions of the survey is which deficits these quality assurance procedures of the battery cell production show. About 74% of the experts agree that it is not possible to completely record the CERs with current optimization measures. About 30% see process-side deficits, 22% production-sided, and 19% see a lack of practical relevance of the quality assurance procedures. What is striking about this question is that all experts agree that there are deficits. Each of the experts names a deficiency or deficit. From this, it can be concluded that there is no sufficient method existing yet. Other approaches prove that Industry 4.0 technologies contribute to improve manufacturing systems by implementing a Cyber Physical System in a machine tool.[28]

Answering the question on the hypotheses whether Industry 4.0 methods make it possible to improve rejection rates a vast majority, more than 65% of respondents, express high to full support for this question.

3.2. Future Battery Generations

All-solid-state batteries are considered as a capable candidate for future applications in EVs and stationary energy storage systems.[29] This new type of battery promises high energy densities combined with a high safety level.[30] However, depending on the type of solid electrolyte, the production process especially for electrode production will be different in comparison with the process steps investigated in this study. As some process steps will be completely different from the current electrode production, the question for future reject rates within ASSB production is asked.[31] Approximately half of the respondents assume that "no significant change" in rejection rates will occur in the future. Almost the same amount of experts assume that there will be waste reductions (18%) or waste increases (26%). In conclusion for ASSB one can say that most experts assume that scrap issues will also play an important role for future battery generations.

4. Discussion of the Results

The relevance of switch-on losses especially for small-scale production and lab series as core result is shown in Figure 2. Although the reject rate in lab series is large the relevance of high yields might be of less importance as for small-scale production with up to 1 GWh output per year. The effort to improve both small-scale and large-scale production sites can be judged high, considering the low overall European production capacity available and the high investments into battery cell production.[32] To be more precise in the analysis of the different production scales the ramp-up procedure has to be considered for the reason that both lab series and small-scale production operate in campaigns with only few numbers of cell. Every campaign is based on a different cell design either only in cell chemistry or for pouch cells possibly furthermore in different dimensions of the battery cell itself. Consequently, a new ramp-up with no changes in the design not necessarily result in high reject as the process parameters should be available from previous runs unless there are no changes in the atmosphere. In general, further research has to focus on the effect of numerous ramp-ups to ensure a low reject in repeated ramp-ups. With regard to flexibility, the result of this analysis is that in small-scale production the potential for the application of data-driven optimization methods is high.

With regard to all production scales, the most relevant process step to focus on is the coating where the highest reject is expected with regard to Figure 3. The 2–5% reject shown in **Figure 4** for coating can limit the turnover. Considering the position of the process step coating in the process chain, it is an early stage process. From an economic perspective, this is even more relevant as an early stage error inhibits a further added value in the following process steps. The production process is dependent on not only the mechanical parameters of the machine but also on the process atmosphere. If both are selected right and the process parameters of the coating step are inside all tolerances the quality of an electrode indirectly depend on the prior mixing step. The material combination in the recipe defines the coating behavior as CER. For instance, all tested samples of the slurry are inside viscosity specification but the slurry is not homogeneous over the whole batch and therefore the thickness in the coating process step varies as a result of changing flow rates through the slot die.[33] For the use of different electrode composition with individual slurry viscosity, the ramp-up process and the associated switch-on losses are relevant to elaborate for all compositions. As this investigation is time consuming a methodology including data-driven control loops to adapt the ramp-up process inline can be integrated.

The experts of the study confirm the hypothesis that the use of Industry 4.0 methods in battery cell production can minimize reject. For an optimization of the production process, the application of quality assurance methods was analyzed and in **Figure 5** where the experts say that Six Sigma and CIP/Kaizen are the most relevant. In addition to these two, a majority is convinced that Industry 4.0 in general can improve the reject rates including other not mentioned methods. There are deficits in all quality assurance procedures and a methodology including data-driven approaches can possibly provide a solution. Moreover, artificial intelligence can be a promising tool to be included in this methodology as it is used in the production of goods to increase the performance of a production plant by means of collected production data or to find an optimal parameter configuration.[34] A system which correlates the monitored process parameters with the quality characteristics and independently learns to adjust the process variables to achieve the quality characteristics is not yet known in battery cell production. The potential for saving switch-on losses in small-scale production is dominant. Overall, however, the experts see high chances of reducing operating losses through methods of Industry 4.0 so that the hypotheses can be fully confirmed.

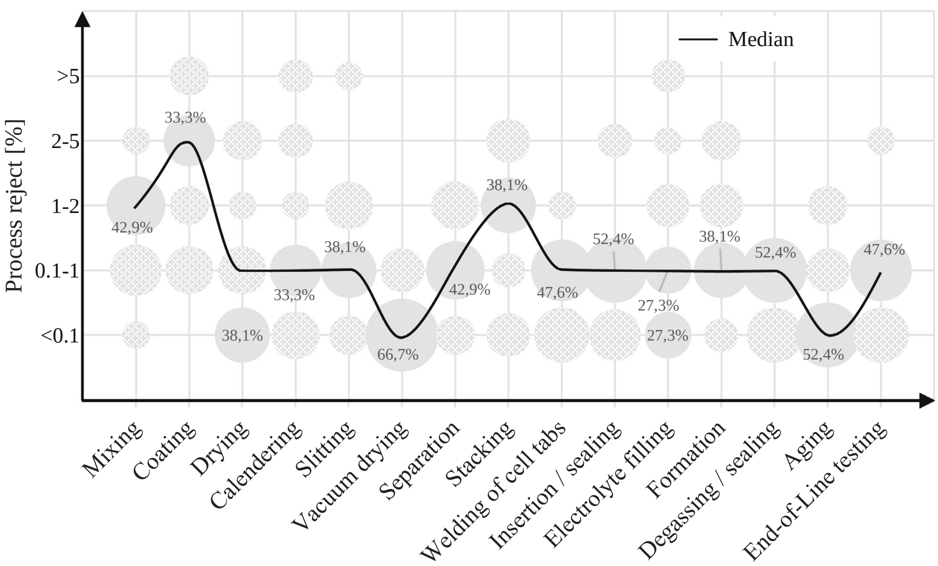

Figure 4. Process reject percentage evaluation at each process step from less than 0.1% to more than 5%.

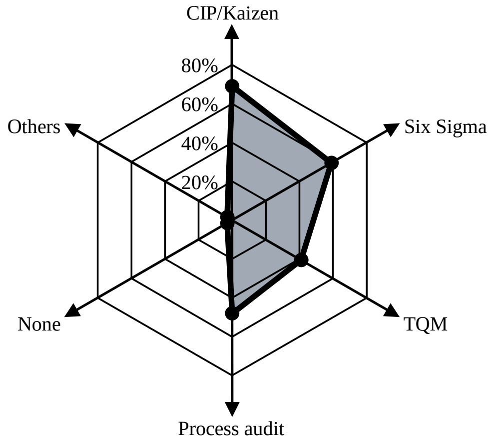

Figure 5. Assumed impact of quality assurance methods on cause-effect relations.

5. Conclusion

As a result, the electrode production and, in particular, the coating process urge a special focus concerning rejects in production. After the last industrial revolution in the 1960s, when electrical and information technology was used to automate production, the next industrial revolution followed. Using Industry 4.0 methods, a new level of flexibility can be achieved by increasing productivity. Based on the experts' opinion, the coating process should first be considered with a focus on reducing rejects by introducing data driven methods. The use of data acquisition tools in battery research facilities such as the eLab in Aachen and the Fraunhofer Research Factory for Battery Cells in Munster will enable data analysis and point out optimization potentials. Further research is needed to concretize the possible applications of Industry 4.0 methods in battery cell production.

The aim is to find out how switch-on losses can be minimized in certain areas of production, for example, using artificial intelligence or how CERs can be analyzed in concrete terms. Therefore, the development of methods has been carried out in further research. A switch-on methodology has to be designed based on three aspects that are divided into the product quality requirements, the analysis of switch-on processes and the design of a method for later implementation.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

battery cell production technologies, electric mobility, quality assurances, ramp-up, reduction of rejects, small-scale production, switch-on losses

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